Cornet Creek Watershed and Alluvial Fan Debris Flow Analysis

Submitted to: Town of Telluride
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MEI Project 07-14.4

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1. INTRODUCTION

The Town of Telluride (Town), located in southwestern Colorado in the San Juan Mountains, has developed around two primary watercourses, the San Miguel River and Cornet Creek. The Town occupies the alluvial fan of Cornet Creek, which drains into the westerly flowing San Miguel River (**Figure 1.1**). Although smaller than the river, Cornet Creek drains an approximately 2.4- mi^2 watershed of high mountainous terrain, and has been responsible for the majority of Telluride's historic flooding problems, consisting primarily of mud and debris flows. Historically, numerous debris flows have occurred along Cornet Creek, with the two most destructive events occurring on July 27, 1914, and August 1, 1969. These events caused deposits of mud and rock with widespread depths of about 2 feet ranging to as much as 6 feet in localized areas (Mears et al., 1974). The most recent flooding event occurred on July 23, 2007, blocked culvert and bridge crossings, and damaged property on the north side of town. Most of the significant flood events have been caused by heavy rainfall following a period of prolonged wet weather.

In addition to delivering large amounts of debris during flood events, Cornet Creek conveys a significant amount of sediment on an annual basis. In recent years, the bed of the creek has aggraded by up to 3 feet in some areas over the period of a single year. In response to this dynamic system, the Town's Public Works Department conducts routine reconnaissance along the creek to identify Town-owned corridors that require sediment removal or present a potential hazard. As well, the Town identifies privately-owned corridors where the Town must coordinate with a property owner to ensure conveyance capacity is maintained or a hazard removed. Reconnaissance takes place prior to, during, and immediately after spring runoff, as well as after unusually intense storm events. All work in and around the creek channel occurs under permits obtained from the U.S. Army Corps of Engineers.

Based on recent needs for the Town to remove accumulated sediment from portions of the channel to maintain an adequate conveyance capacity, a decision was made by the Town to obtain more specific information regarding the appropriate level of excavation in the creek and to provide information about state-of-the-art flood warning systems. Mussetter Engineering, Inc. (MEI) was selected by the Town of Telluride to conduct detailed hydrologic, hydraulic, and sediment-transport analyses of Cornet Creek in order to investigate and provide recommendations regarding the following items:

1. Development of an appropriate channel grade to maintain or improve capacity without inducing further channel instability,
2. Impact assessment of the recently replaced North Townsend Street Bridge and of replacing/improving low capacity culverts at Dakota and Pacific Avenues on flooding potential, and
3. Evaluation of the potential for debris flows to occur along Cornet Creek and the investigation of potential debris-flow mitigation techniques and early-warning systems.

The results of the investigations and the ensuing recommendations were presented to the Town in a report entitled, *Cornet Creek Drainage Maintenance and Flood Mitigation Study, Colorado* (MEI, 2008). As a result of the initial investigation, the Town requested that MEI conduct a

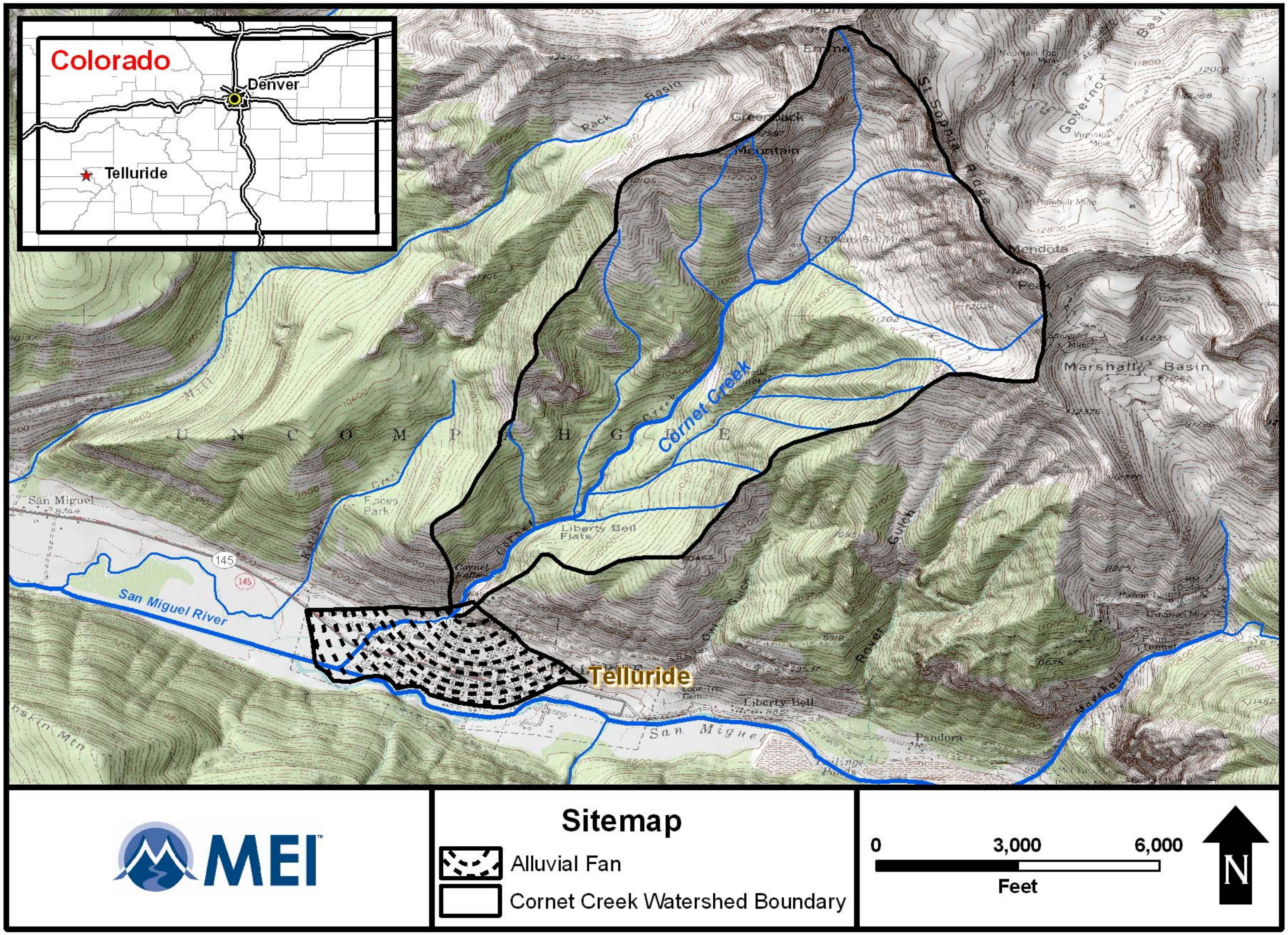

Figure 1.1. Vicinity map of Telluride showing the general location of the study reach.

follow-up study, the *Cornet Creek Watershed and Alluvial Fan Debris-flow Analysis* that is the subject of this report. The objectives of the study were to:

1. Estimate the magnitude of potential debris-flow events originating from the Cornet Creek watershed,

2. Delineate approximate extent of the debris-flow hazard area and potential deposition depths along the Cornet Creek alluvial fan within the Town, and

3. Expand upon the initial evaluation of potential debris-flow mitigation measures or installation of early-warning systems conducted as part of the Cornet Creek Drainage Maintenance and Flood Mitigation Study.

1.1. Scope of Work

To accomplish the above objectives, the following tasks were performed.

Task 1: Obtain and review current available information and data, including previous debris-flow studies of Cornet Creek, and current state-of-the-art debris-flow estimation and monitoring techniques.

Task 2: Develop a detailed 2-D hydraulic model of Cornet Creek and the adjacent alluvial fan using a FLO-2D model, which is specifically designed to model debris-flow conditions, based on the 2003 2-foot contour mapping and the detailed channel survey data collected in 2007 by Foley Associates, Inc. (FAI). The downstream limit of the hydraulic model will be along the boundary of the Cornet Creek alluvial fan and the San Miguel River, and the model will extend approximately 0.5 miles upstream to the mouth of the canyon.

Task 3: Conduct a 2-D debris-flow analysis over a range in magnitude of no more than three potential debris-flow events originating from the Cornet Creek watershed. This analysis will be performed using FLO-2D, which will provide information regarding the potential depth and velocities of the debris flow as well as the estimated extent of inundation. Given the variability of sediment volumes associated with debris flows from this watershed, a review of the hydrology developed as part of the Cornet Creek Drainage Maintenance and Flood Mitigation Study will be performed in conjunction with historic and future estimates of potential debris-flow volumes in order to provide the Town with estimated depositional impacts from three debris-flow events of varying magnitude.

Task 4: Expand upon the preliminary recommendations regarding potential debris-flow mitigation options and early-warning systems initially developed as part of the Cornet Creek Drainage Maintenance and Flood Mitigation Study.

Task 5: Prepare draft and final technical reports describing the methods, assumptions, and the results of the debris-flow analysis, and provide recommendations for monitoring and mitigating debris flows in the system.

Task 6: Participate in one meeting with Town staff and elected officials regarding the various elements of the study.

Information from the previous study (MEI, 2008), including the outflow hydrographs, cross-section geometry and designed channel geometry, were used to develop the FLO-2D model for this study. Based on discussions with the Town staff, the debris-flow analysis was performed for the following scenarios:

1. 25-year peak flood event on Cornet Creek with the Townsend Street culvert blocked

2. 25-year peak flood event on Cornet Creek with all culverts and bridges blocked

3. 10-year peak flood along the east-side of the alluvial fan (flow path of the 1914 debris flow).

1.2. Authorization and Study Team

This study was performed by MEI under a contract with the Town of Telluride Public Works Department. The Town's Project manager is Ms. Karen Guglielmone. Dr. Michael Harvey was MEI's Principal Geomorphologist and Project Manager. Messrs. Chad Morris, P.E. (CO) and Dai Thomas, P.E. (CO) were MEI's project engineers.

2. HISTORICAL EVENTS AND MODELING

2.1. Existing Studies and Background Material

Historic reports and information that were provided by the Town of Telluride or that were obtained directly from other sources by MEI were reviewed. Information from previous studies along Cornet Creek and the San Miguel River were also considered. Specific reports that were considered include the following:

1. Report of FLO-2D mudflow modeling of the Cornet Creek alluvial fan that was developed for a Flood Insurance Study (FIS) by Simons, Li and Associates and Dr Jim O'Brien, (SLA and O'Brien, 1989a).

2. Report on "Flood Hazard Delineation on Alluvial Fans and Urban Floodplains" (O'Brien and Lenzotti & Fullerton Consulting Engineers, Inc, 1989).

3. Two-foot elevation contour mapping of the Town of Telluride developed by Foley and Associates (2003).

4. Geomorphic, sedimentologic, hydraulic and sediment-continuity reports prepared by MEI for the San Miguel River (MEI, 1998) and Cornet Creek (MEI, 2008).

For the purposes of this study the NRC (1982) terminology for describing debris flows and other forms of hyper-concentrated flows has been adopted. The National Research Council Committee (NRC, 1982) proposed four categories to delineate the continuum of types of sediment transport: water floods, mud-floods, mudflows, and landslides, and did not include the term debris flow because it was considered to be too non-specific. Hyper-concentrated flows emanating from the Cornet Creek watershed are categorized as mudflows, and these have sediment concentrations by volume in the range of 47 to 77 percent (Costa, 1988).

2.2. Mudflow Characterization and Processes

Hyperconcentrated sediment flows (mudflows and mud floods) are part of a continuum in the "physics of flowing water and sediment movement that ranges from clear water flow to mass wasting processes (landslides)" (SLA and O'Brien, 1989). In general, the sediment transport characteristics in the continuum range from suspended and bed load transport in water floods to mass wasting in landslide events. The National Research Council Committee (NRC, 1982) proposed four categories to delineate this continuum: water floods, mud floods, mudflows, and landslides (**Table 2.1**). The bounds of each of these categories can be approximated based on the fluid properties, and in particular by the sediment concentration (by volume) of the fluid (**Figure 2.1**).The sediment concentration of fluid is defined as the ratio of the sediment volume to the water volume and is given by:

$$C_V = \text{Volume of Sediment} / (\text{Volume of Water} + \text{Volume of Sediment})$$

The continuum indicates that water floods are mostly comprised of water with some sediment (low concentration of sediment), whereas, landslides are mostly comprised of bulk sediment with some water (high concentration of sediment). The concentration of the sediment is an important component in determining the physical processes that govern the behavior of the fluid-sediment mixture in each of these categories. For example, the flow characteristics of a mud flood are dominated by the turbulent and viscous forces within the fluid matrix, whereas, movement of a landslide is dominated by the dispersive stresses and particle friction.

This study focuses on the sediment transport characteristics of the mud flood and mudflow categories; however a brief description of the sediment transport characteristics of the water floods and landsliding events is presented for the purpose of describing the bounding categories.

Table 2.1. Mudflow Behavior as a Function of Sediment Concentration (FLO-2D manual, 2006).

	Sediment Concentration		Flow Characteristics
	by Volume	by Weight	
Landslide	0.65 - 0.80	0.83 - 0.91	Will not flow; failure by block sliding
	0.55 - 0.65	0.76 - 0.83	Block sliding failure with internal deformation during the slide; slow creep prior to failure
Mudflow	0.48 - 0.55	0.72 - 0.76	Flow evident; slow creep sustained mudflow; plastic deformation under its own weight; cohesive; will not spread on level surface
	0.45 - 0.48	0.69 - 0.72	Flow spreading on level surface; cohesive flow; some mixing
Mud Flood	0.40 - 0.45	0.65 - 0.69	Flow mixes easily; shows fluid properties in deformation; spreads on horizontal surface but maintains an inclined fluid surface; large particle (boulder) setting; waves appear but dissipate rapidly
	0.35 - 0.40	0.59 - 0.65	Marked settling of gravels and cobbles; spreading nearly complete on horizontal surface; liquid surface with two fluid phases appears; waves travel on surface
	0.30 - 0.35	0.54 - 0.59	Separation of water on surface; waves travel easily; most sand and gravel has settled out and moves as bed load
	0.20 - 0.30	0.41 - 0.54	Distinct wave action; fluid surface; all particles resting on bed in quiescent fluid condition
Water Flood	< 0.20	< 0.41	Water flood with conventional suspended load and bed load

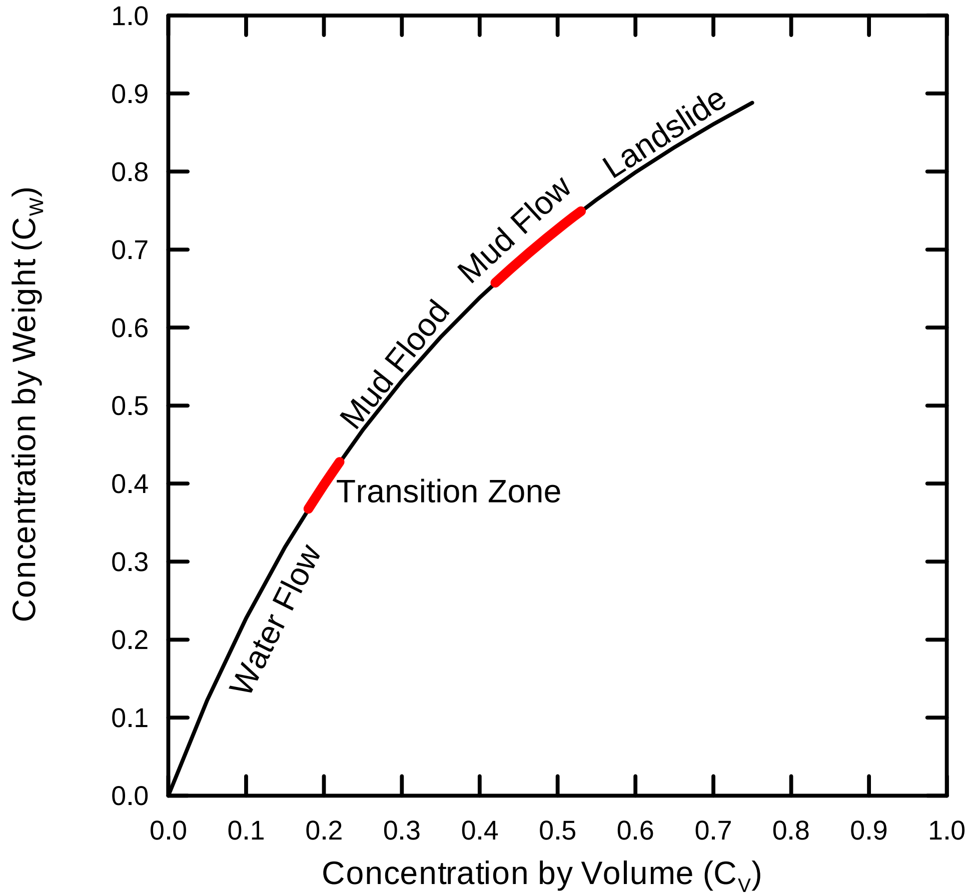

Figure 2.1. Classification of hyperconcentrated sediment flows (modified from FLO-2D Manual, 2006).

Flood flows generally have sediment concentrations of less than 20-percent (by volume). They are essentially water floods with high bed load and suspended loads where the bed load may be affected by the high concentration of suspended load (i.e. fine sediment wash load). The sediment transport characteristics of water floods are modeled using conventional bed-load and suspended load formulas and methodologies.

Landslides generally have sediment concentrations greater than 55 percent (by volume) and are considered as bulk solid movement as opposed to fluid motion. Landslides may range from slow moving earth flow and creeping soil masses to rapid rotation or slippage failures.

Hyper-concentrated sediment flows are defined as flood events with sediment concentrations that range between approximately 20 and 55 percent by volume, however, the sediment concentration for a given event is generally considered to be between 20 and 45 percent (O'Brien, 2004). The fine sediment concentration (silt, clay and fine sands in the fluid matrix) controls the properties of the fluid, including, viscosity, density, and yield stress. Mudflows are non-Newtonian and they have much higher viscosities and densities compared to water flows. These properties result in mudflows having significantly slower velocities compared to water floods on the same slope. The fine sediments increase the density of the fluid matrix, which increases the buoyancy of sediments thereby creating conditions that allow gravel to boulder-sized material to be transported near the flow surface by mudflows. The yield stress is a measure of the internal fluid resistance to flow and affects both the initiation and cessation of flows. For the purposes of this report, all hyper-concentrated sediment flows (mud floods and mudflows) will be referred to as mudflows.

The sediment matrix of a hyper-concentrated flow is non-homogeneous and the sediment properties change significantly as they flow down steep watershed channels or across alluvial fans. As the mudflow moves over the alluvial fan, dewatering of the fluid matrix can occur by infiltration and escapement to the surface. This may further increase the concentration of the hyper-concentrated sediment flows and alter the transport characteristics of the flow. "Almost all hyper-concentrated sediment flows are fully turbulent, unsteady and non uniform, and are characterized by surging, flow cessation, blockage, and roll waves" (SLA and O'Brien, 1989).

During a mudflow event, the average sediment concentration over the duration of the hydrograph generally ranges between 20 and 35 percent by volume with peak concentrations approaching 45 percent (Table 2.1 and Figure 2.1). Large flood events such as the 100-year flood may contain too much water to produce a viscous mudflow event. Lower recurrence interval rainfall events such as the 10- or 25-year return period storm may have a greater propensity to create viscous mudflows. Most watersheds with a history of mudflow events will eventually develop a sediment supply in the channel bed such that even relatively small rainfall-runoff storms may generate mudflow surges. In general, mudflows have a distinct pattern of flood evolution. Initially, clear water flows from the basin rainfall-runoff may arrive at the fan apex. This may be followed by a surge or frontal wave of mud and debris (40- to 50-percent concentration by volume). When the peak arrives, the average sediment concentration generally decreases to the range of 30 to 40 percent by volume. On the falling limb of the hydrograph, the sediment concentration decreases due to the reduced availability of sediment, however, surges of higher sediment concentration may occur.

2.3. FLO-2D Model

FLO-2D is a 2-dimensional (2-D) hydraulic model that was developed to perform both clear-water and hyper-concentrated sediment flow-routing in channels and/or on alluvial fans with an unconfined flow path. The model utilizes a volume conservation scheme to simulate both sub-critical and super-critical flows in the channel or floodplains, as well as flows exiting from the channel to the floodplain and vice versa. Overland flow is modeled using a 2-D diffusive wave approximation of the momentum equation and the channel flow is modeled 1-dimensionally using the momentum equation. A central difference routing scheme with eight potential flow directions is used to simulate the progression of the floodwave hydrograph over a system of square grids.

The FLO-2D model contains several components that are used to represent and model the complex topography and processes, including: channel-floodplain flow exchange, loss of storage due to buildings, flow obstructions, simulation of hydraulic structures, simulation of street flow and simulation of hyper-concentrated sediment flows (mudflows). Hyper-concentrated sediment flow is simulated by the FLO-2D model using a quadratic rheological model that includes viscous stress, yield stress, turbulence, and dispersive stress terms as a function of sediment concentration. FLO-2D does not have the ability to model unsteady phenomena such as surging. It also assumes a rigid boundary, and therefore, does not model aggradation or scour.

2.4. Previous Mudflow Modeling

A MUDFLOW model (an earlier version of the FLO-2D model) of the Cornet Creek alluvial fan was developed by SLA and O'Brien (1989a). This model has a grid resolution of 300 feet (approximately one city block) and contained 95 grid elements. The MUDFLOW model did not have the ability to represent streets, whereas the more recent FLO-2D model has additional components including the ability to simulate flows and storage along streets and roads using the Streets module. The inflow sediment hydrograph for the MUDFLOW model was calibrated to the 1969 flood by adjusting the concentration and timing of the sediment so that the predicted total hydrograph volume and extent of flooding (at the 25-year recurrence interval) matched the 1969 flood. The inflow clearwater hydrograph for the MUDFLOW model had peak discharges of 473 and 700 cfs for the 10- and 25-year return interval, respectively.

A refined MUDFLOW model with a grid resolution of 25-feet was developed as a supplemental study (SLA and O'Brien, 1989b) to the previously mentioned report. This model was developed using more recent topographic data than was available for the original MUDFLOW model. The model extended approximately 375 feet downstream from the apex of the fan and was developed to provide more detailed results near the apex of the fan.

2.5. Historic Mudflows on the Cornet Creek Alluvial Fan

Two significant mudflow events on the Cornet Creek alluvial fan have been documented. The first occurred in July 27, 1914, and killed one person and injured many others (San Miguel Examiner, unknown date). The Telluride Journal (July 28, 1914) reported the following: "*at 12:50 p.m. Monday afternoon, July 27, 1914, following on the heels of one of the hardest rainstorms experienced in the city, a river of mud, very conservatively estimated at between 8 and 10 feet in height, swept out of Cornet Creek canyon, just north of town." "A waterspout of unbelievable volume, resulting from a cloudburst near the top of the Sawtooth Range, directly north of Town, was the source of the flood, and water flowing from the pinnacle point of the range, almost due north of the Liberty Bell mine workings, and gathering momentum in its mad race through the Cornet Creek Canyon."* **Figure 2.2** shows the extent of the mudflow deposits for the 1914 flood. The mudflow was deposited primarily along the eastern side of the alluvial fan and extended from Oak Street, eastwards to approximately Alder Street (Figure 2.2). The depth of the sediment deposits were estimated at approximately 8 feet near the mouth of the Canyon and were 2 to 4 feet at Colorado Avenue (**Figure 2.3**). It was estimated that boulders in excess of 20 tons were transported during the 1914 flood (**Figure 2.4**). A berm had been constructed at the mouth of the canyon in the early 1900's to divert flows away from the eastern and central portions of town. The berm was constructed of earth and rocks and it was approximately 100 feet in length and 8 to 10 feet high. The berm was washed out during the 1914 flood and was subsequently rebuilt and it still exists.

The second significant mudflow event occurred on August 1, 1969. The Telluride Times reported: *"It has been a wet summer in San Miguel County. Shortly after 2:00 pm, severe rumblings were heard from the mountains in the general vicinity of the Old Liberty Bell workings. Between 2:30 and 2:45 pm, a stream of mud load with boulders, tree trunks, and debris was observed coursing from Cornet Creek. A clock, demolished in the flood was found to have stopped at 2:34 p.m."*

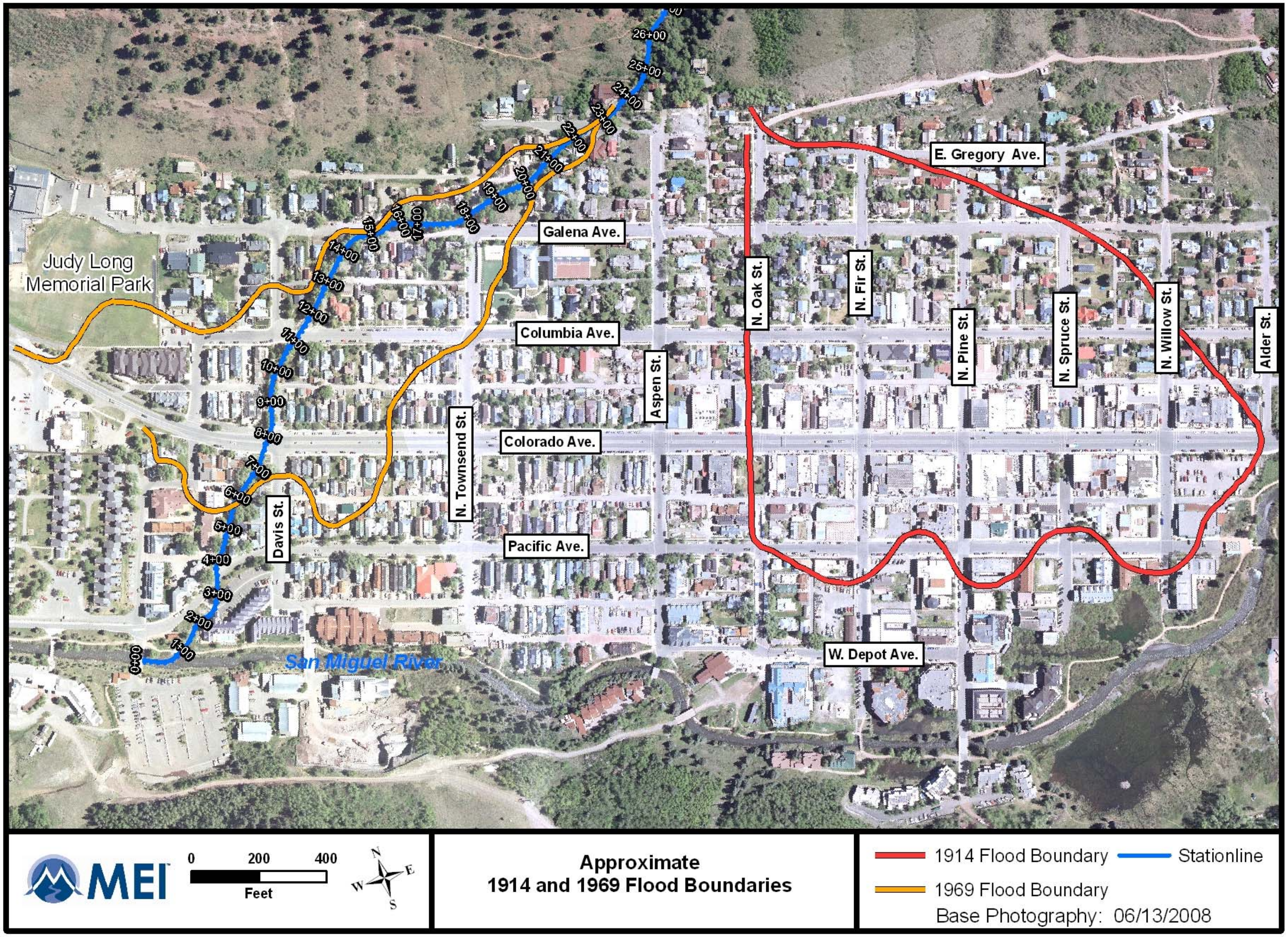

Figure 2.2. Deposition limits of the 1914 and 1969 Cornet Creek mudflows (SLA, 1989).

Figure 2.3. Mudflow deposits during the 1914 event.

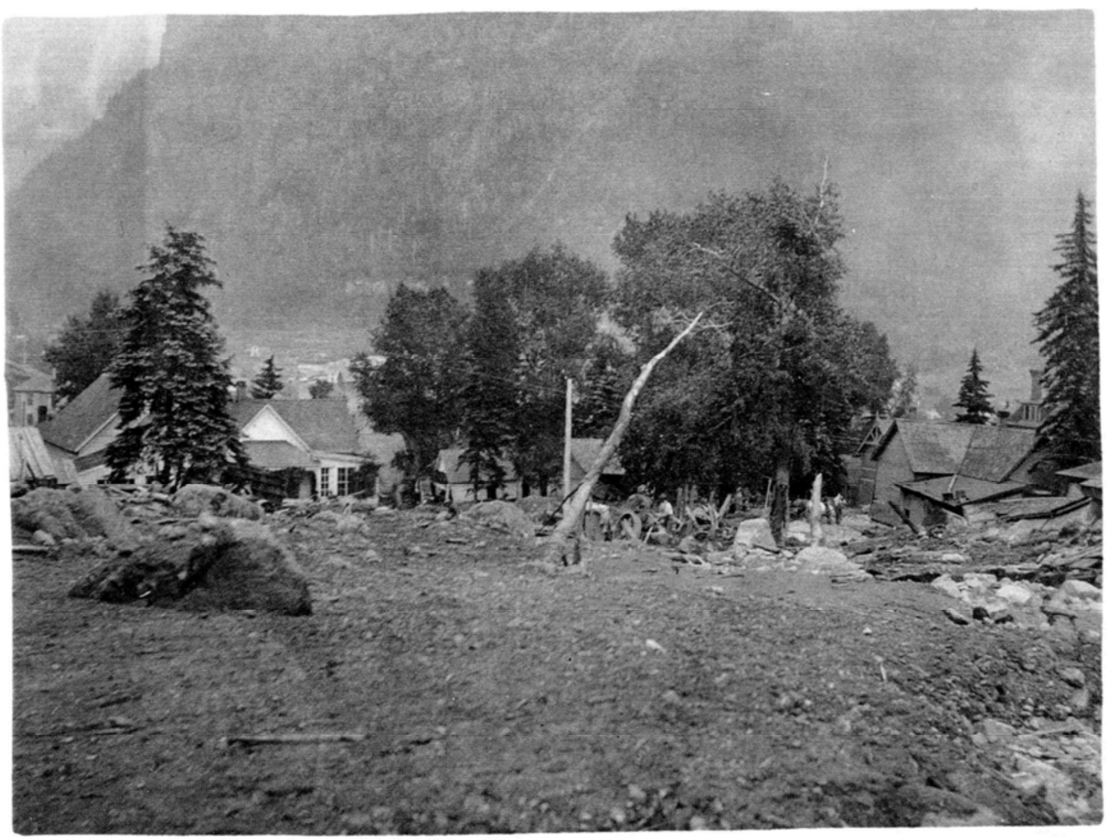

Figure 2.4. Mudflow deposits from the 1914 event. Note the size of the boulders transported and deposited by the mudflow.

Sediment deposition from the 1969 event was mostly along the western side of the alluvial fan and it was generally aligned with Cornet Creek (Figure 2.2). The depth of sedimentation ranged from approximately 3 feet at Galena Avenue and decreased to approximately 1 foot midway between Columbia Avenue and Colorado Avenue. The estimated volume of sediment was approximately 680,000 ft^3 (25,185 yd^3) based on high flow marks, photographs, inundation mapping, and eyewitness accounts of the event (SLA and O'Brien, 1989).

3. FLO-2D Modeling

A FLO-2D model of the Cornet Creek alluvial fan was developed to delineate the flood-hazard area resulting from mudflows originating from the Cornet Creek watershed for the following scenarios:

1. 25-year peak flood along the west-side of the alluvial fan with the Townsend Street Culvert blocked on Cornet Creek.

2. 25-year peak flood along the west-side of the alluvial fan with the all culverts and bridges blocked on Cornet Creek.

3. 10-year peak flood along the east-side of the alluvial fan (flow path of the 1914 flood).

The results of the modeling were used to develop maps that show: the depth and extent of flooding, the maximum flow velocities and the hazard potential for each of the various scenarios.

3.1. FLO-2D Model Development

3.1.1. FLO-2D Grid

A FLO-2D model of the Cornet Creek alluvial fan was developed that extends from the apex of the Cornet Creek fan downstream to across the San Miguel River and from approximately 500 feet west of Mahoney Drive to North Maple Street on the east side of town (**Figure 3.1**). The model has a 50-foot grid size and contains 4,200 elements. For the purposes of the modeling, the FLO-2D grid was rotated 18 degrees counter clockwise to align the FLO-2D grid with the alignment of the streets.

The Grid Developer System (GDS), which is part of the FLO-2D model, was used to assign elevations to each of the grid elements using the 2003 2-foot contour interval mapping provided by the Town of Telluride. The elevation of Cornet Creek at the apex of the alluvial fan is approximately 9,016 feet and the elevation at the confluence of the San Miguel River is approximately 8,725 feet (elevation difference of 291 feet).

3.1.2. Channel Cross Sections

Channel cross sections assigned to the main channel grid elements were obtained from the previously developed HEC-RAS model of Cornet Creek (MEI, 2008). The HEC-RAS model was developed using survey data collected by Foley and Associates, Inc. in July and October 2007. The hydraulic output from the HEC-RAS model was used to perform a channel stability analysis. Results of the channel stability analysis recommended clearing sediment from the channel to provide greater conveyance capacity, especially around the channel-spanning structures. In addition, a stable channel design with new cross-section geometry was developed to represent removal of sediment in the upper section of Cornet Creek. The Town removed the sediment from the channel to the design elevations in the summer of 2008. The cross-sections from the HEC-RAS model and the excavated cross sections were used to develop the FLO-2D channel cross sections. At channel grids where no surveyed cross sections were available, the cross sections were interpolated between surveyed cross sections using the PROFILES program included in FLO-2D.

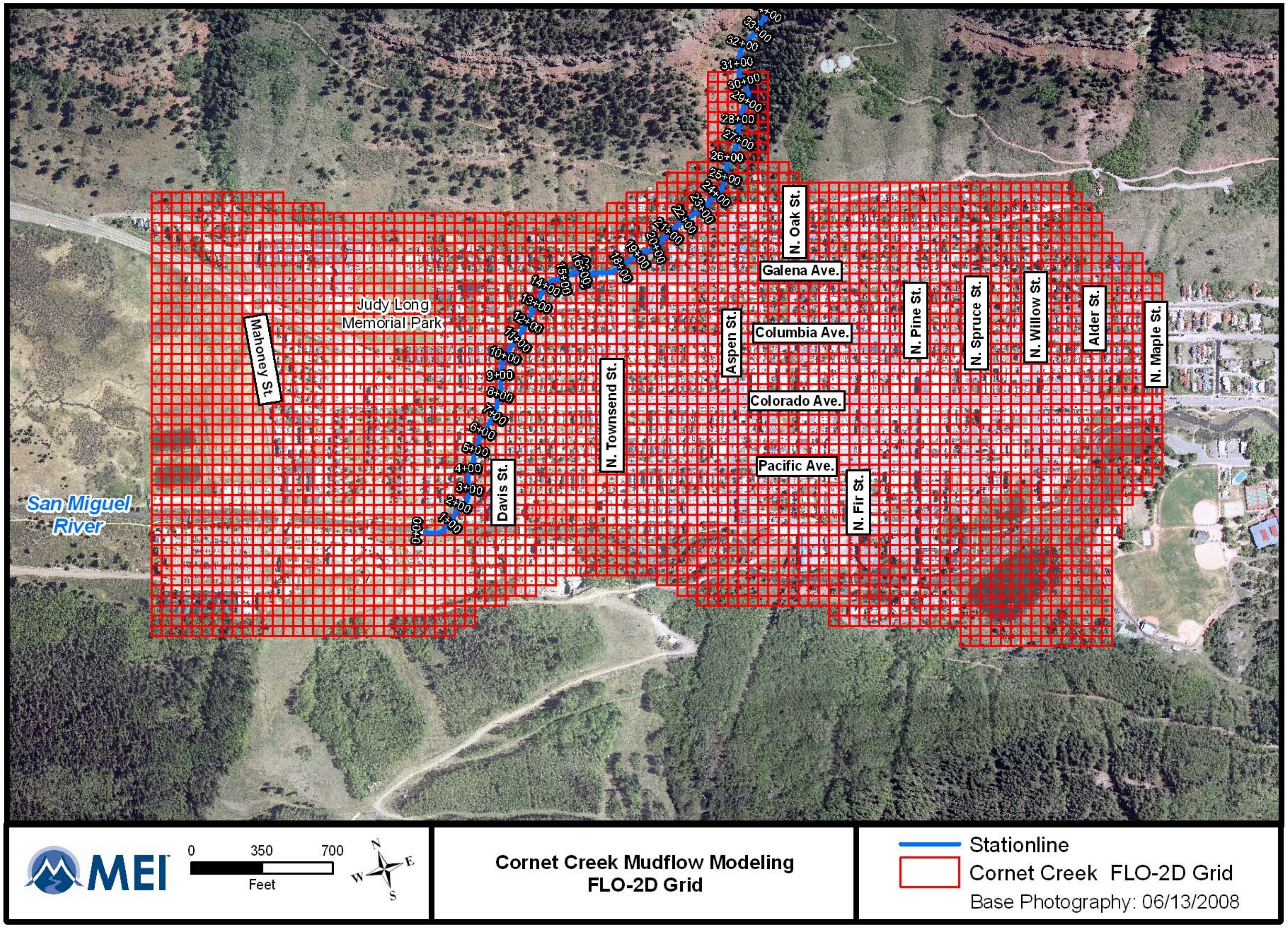

Figure 3.1. Extent of 50-foot FLO-2D grid.

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3.1.3. Bridges and Culverts

Hydraulic rating curves were developed for the FLO-2D model to represent the stage-discharge conditions at the bridges and culverts for free-flowing and blocked flow conditions. The stage-discharge relationships for the free-flowing structures were obtained from the output of the HEC-RAS model that incorporated the stable channel design geometry. The stage-discharge relationships for the blocked structures were developed by modifying the geometry of the HEC-RAS model to represent complete blockage of the culvert and/or bridge openings. The weir flow option was utilized in HEC-RAS to develop the stage-discharge rating curves on the upstream side of the blocked structures. **Figure 3.2** shows the locations of the hydraulic structures represented in the FLO-2D model.

3.1.4. Channel and Overbank Roughness Values

Channel roughness values in the FLO-2D model were selected to match the calibrated HEC-RAS model with Manning's n-values ranging from 0.04 to 0.07. Overbank roughness values were selected using the Arcement and Schneider (1989) method and *n*-values ranged from 0.04 for Urban/Industrial areas to 0.10 for dense vegetation (**Figure 3.3**, **Table 3.1**).

Table 3.1. Summary of overbank roughness values.

Description	Manning's *n*-value
Urban / Industrial (Limited Vegetation)	0.04
Open Ground / Few Structures	0.05
Urban / Residential (Moderate Vegetation Density)	0.07
Low Density Residential with Moderate Vegetation	0.08
Dense Residential with Minor Vegetation	0.08
Riparian Corridor / Dense Vegetation	0.10

3.1.5. Streets

Street elements are assigned to the FLO-2D model to represent the elevation and roughness characteristics of the street. Street elements typically have different conveyance and storage properties compared to the floodplain elements. Street elements are important as they act as conduits for conveying flood flows and have the ability to store sediment. Street widths and elevations were measured from the 2003 topographic mapping. The curb heights of the streets were estimated based on the 2003 topographic survey and aerial photographs. Generally, the curb height was set at 0.4 feet for the streets that were observed to have a curb and gutter. The curb height of 0.4 feet was estimated as the average depth across the street that varies in depth from gutter of the street to the crown of the street. The curb height was set at 0 feet in locations were there was no observable storage in the street; this occurred mostly in the residential areas that do not have sidewalks. Street elements were assigned to locations that do not have curb and gutters, in order to represent the observed lower roughness values and higher Froude numbers that can occur on streets as compared to the remainder of the alluvial fan. A Manning's *n*-value of 0.020 was assigned to the street elements and the Froude numbers were limited to 1.5 in the FLO-2D model.

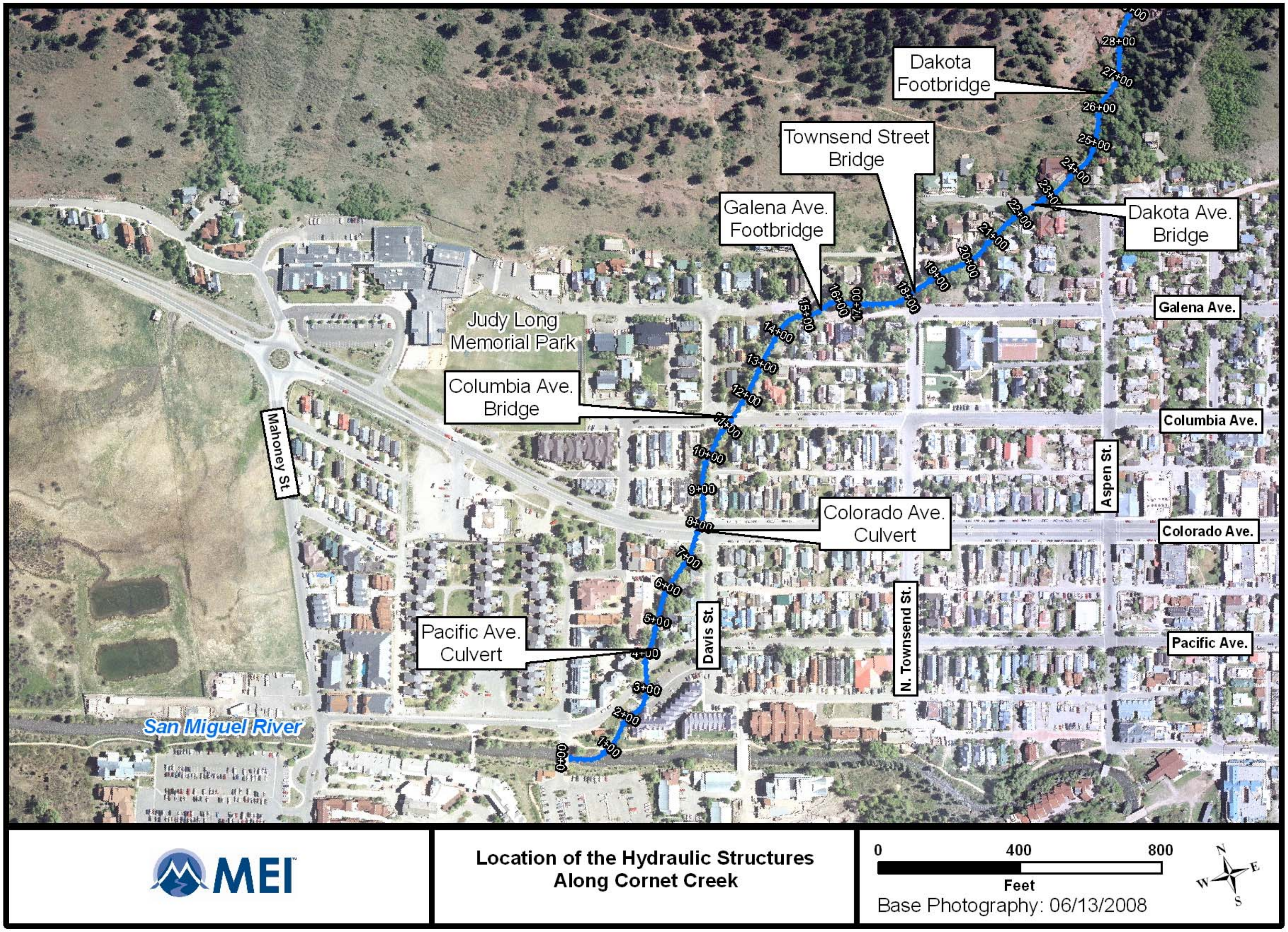

Figure 3.2. Location of the hydraulic structures along Cornet Creek.

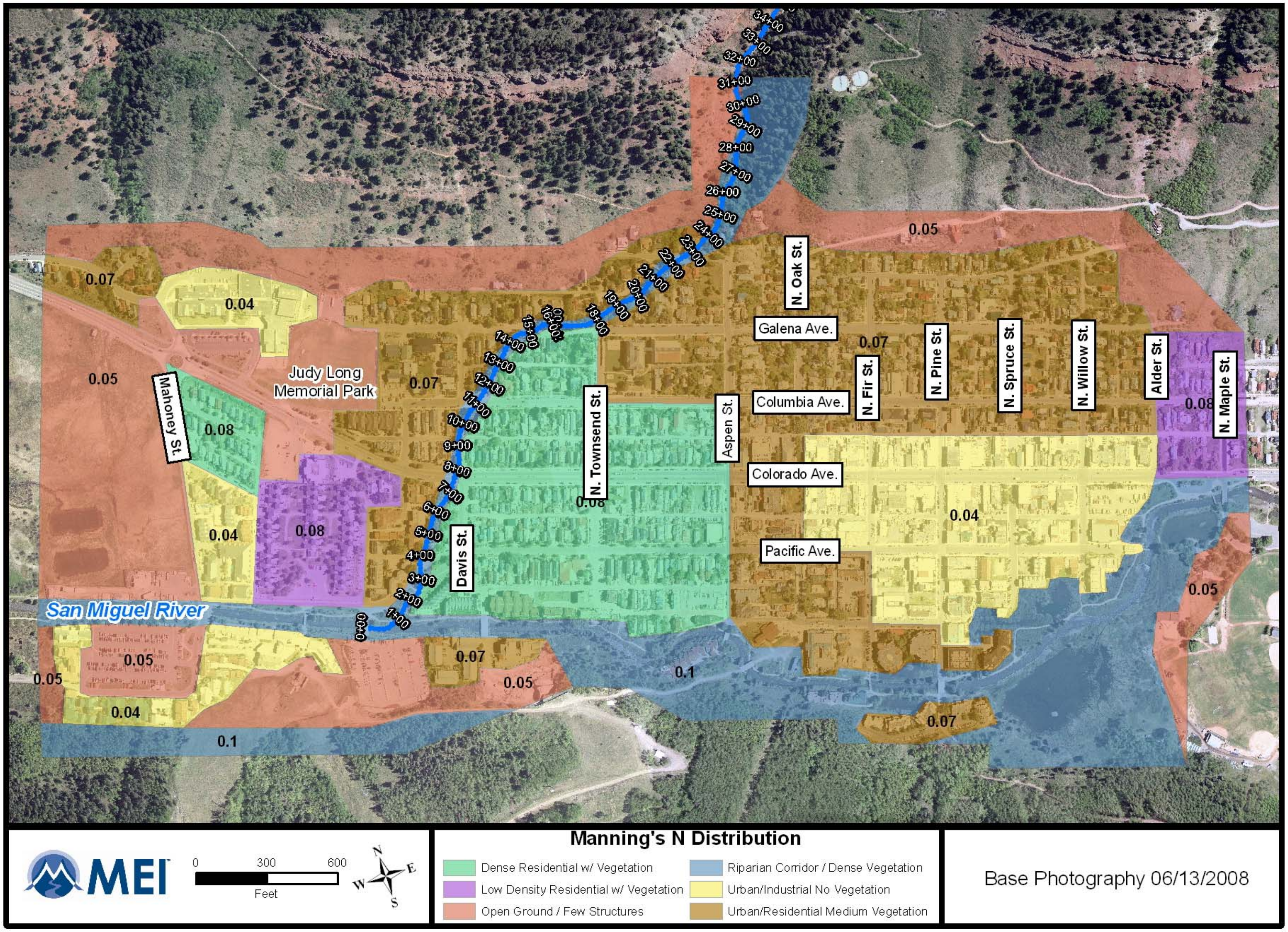

Figure 3.3. Distribution of Manning's *n*-values applied to the FLO-2D model.

3.1.6. Width Reduction Factors and Area Reduction Factors

Width reduction factors (WRFs) and area reduction factors (ARFs) are assigned to the FLO-2D grid elements to represent the blockage of flow paths and reduction in storage that predominantly occurs due to the presence of buildings. Width reduction factors are applied to represent the blockage of flow through the side of an element, while ARFs represent the loss of floodplain storage volume due to the buildings. For example, a wall might obstruct 40 percent of the flow width of a grid element side and a building could cover 75 percent of the same grid element. The ARFs and WRFs were computed using ArcGIS by overlaying the building outlines on the FLO-2D grid (**Figure 3.4**).

3.1.7. Clearwater Flow Hydrographs

The clearwater inflow hydrographs for the FLO-2D model were obtained from the results of the previously completed hydrologic analysis of the Cornet Creek watershed (MEI, 2008). A rainfall-runoff model (HEC-HMS) was developed to estimate the hydrographs for the 2-, 5-, 10-, 25-, 50- and 100-year flood events at the mouth of the Cornet Creek basin. The flood hydrographs were computed using a 24-hour storm duration with peak rainfall intensity at 6 hours. The peak flow for the 2-, 5-, 10-, 25-, 50- and 100-year flood events are 287, 482, 659, 915, 1,176, and 1,491 cfs, respectively, and the runoff volumes are 30, 47, 65, 84, 106, and 121 acre-feet, respectively (**Table 3.2**). The shape of the hydrographs is representative of the localized thunderstorm events that occur in the area and of those that initiated the 1914 and 1969 mudflows. The thunderstorm events are characterized by short-duration (less than 30 minutes) and high intensity, and are followed by rainfall of decreasing intensity.

Table 3.2. Summary of computed peak discharges and flow volumes entering the Town of Telluride from the Cornet Creek watershed, based on HEC-HMS model results.

Recurrence Interval (yrs)	Annual Probability of Occurrence (%)	Peak Discharge (cfs)	Storm Event Volume (ac-ft)
2	50	287	30
5	20	482	47
10	10	659	65
25	4	915	84
50	2	1,176	106
100	1	1,491	121

The 10- and 25-year hydrographs were simulated in the FLO-2D model as these smaller rainfall events have greater propensity to create viscous mudflows. For the purposes of the FLO-2D modeling, the duration of the hydrographs was reduced in length from 12 to 3 hours, by removing the low flows that occur at the beginning and end of the hydrographs. The resulting hydrographs (**Figure 3.5**) have peak flows that occur at 0.42 hours compared to 6 hours in the HEC-HMS model, and have runoff volumes of 37 and 49 ac-ft, respectively, for the 10- and 25-year events, compared to 47 and 65 ac-ft in the HEC-HMS model.

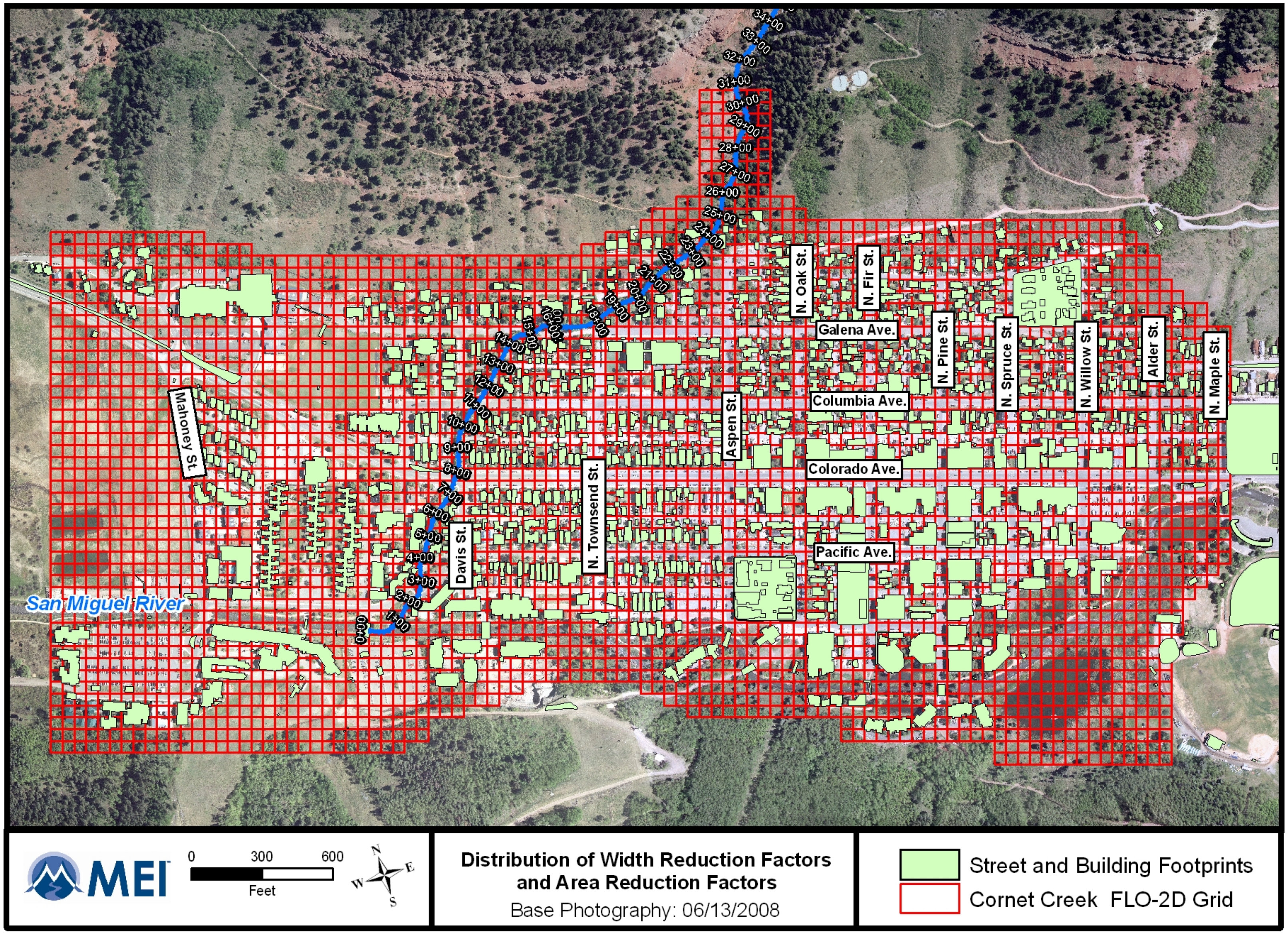

Figure 3.4. Distribution of width reduction factors and area reduction factors to the FLO-2D model.

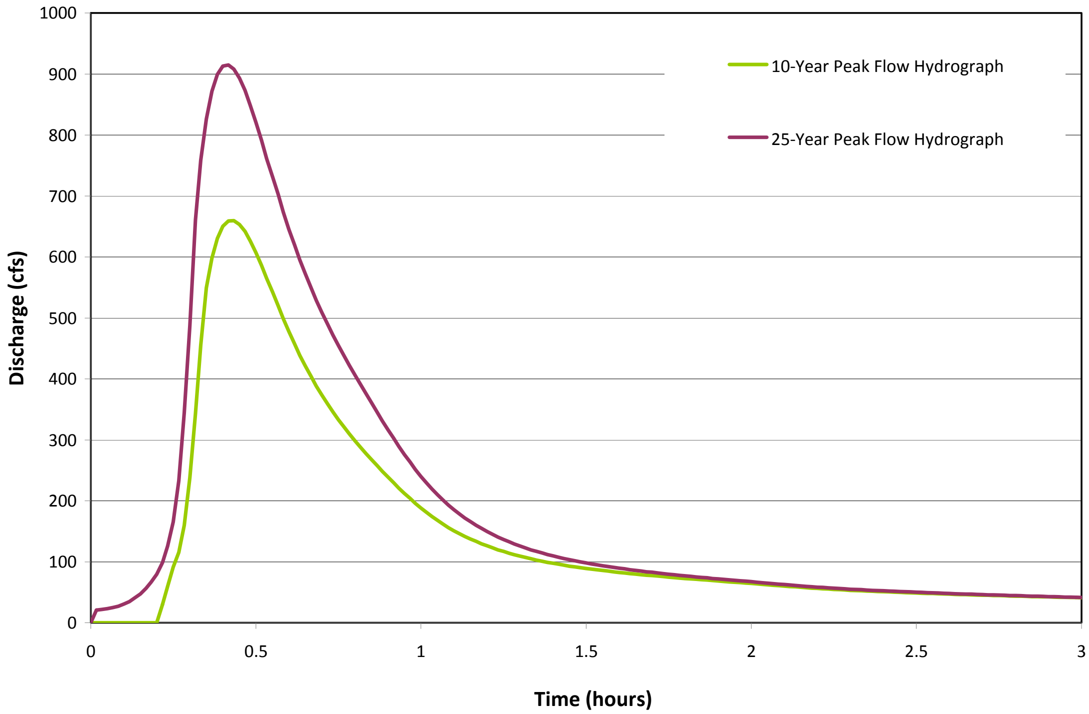

Figure 3.5. Developed hydrographs for the 10- and 25-year peak flow events.

3.1.8. Mudflow Hydrographs

Determination of the recurrence interval of hyper-concentrated sediment flow events is difficult due to the complex relationships between rainfall, antecedent soil moisture conditions and availability of sediment. Antecedent moisture conditions can influence whether a mudflow event will occur for a given rainfall event. For example, a 25-year rainfall event may initiate a mudflow if the soils are saturated, whereas the same 25-year rainfall event will not initiate a mudflow if the soils are not saturated. Antecedent moisture conditions can also effect soil erosion, bank and slope stability, and the magnitude and timing of runoff.

The availability of stored sediment in the basin affects the magnitude and characteristic of the hyper-concentrated sediment flow events. In addition, the time elapsed since the last major flow event also affects the quantity of sediment stored in the channel and watershed which is available to produce a mudflow. Given that the last major event was in 1969 (40 years ago), the highly erodible nature of the sediment in the basin, and field observations of the basin, there appears to be sufficient sediment stored in the basin to create another event, given the right localized rainfall event and antecedent soil conditions.

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Given the complexity of assigning a return interval to mudflow events, the frequency of a mudflow was conservatively assumed to be equal to the probability of the exceedence for the rainfall. This assumption is reasonable considering that the probability of exceedence of mudflows can be no greater than that for the rainfall.

The clear-water inflow hydrograph is input to the FLO-2D model at a specified element near the head of the Cornet Creek debris fan. The clearwater hydrograph is then bulked with sediment using a developed sediment concentration (by volume, C_V) hydrograph to represent the mudflow hydrograph. The total volume of the water and sediment in a mudflow can be determined by multiplying the clearwater volume by the bulking factor, where the bulking factor is defined by:

$$BF = 1/(1 - C_V)$$

For example, a sediment concentration of 10 percent (C_V=0.10) creates a bulking factor of 1.11, indicating the flood volume is 11 percent greater than if the flood was considered to be only water.

The sediment concentration hydrograph was developed to represent the likely variation in sediment concentration throughout the storm hydrograph based on previous studies and recommendations provided in the FLO-2D manual.

The developed sediment concentration hydrograph (**Figure 3.6**) was used for both the 10- and 25-year mudflow simulations and has the following characteristics:

1. The initial rising limb and the last part of the recessional limbs of the hydrographs have a sediment concentration of 20 percent, which corresponds to the minimum concentration for a mudflow.

2. The steep rising limb of the hydrograph is bulked to a maximum concentration of 45 percent to simulate the frontal wave of the mudflow. The peak of the sediment concentration hydrograph occurs 6 minutes before the peak of the clearwater hydrograph.

3. The sediment concentration at the peak of the clearwater hydrograph is less than the peak sediment concentration in order to simulate water dilution.

4. The average sediment concentration over the period of the hydrograph is 29 percent.

The developed hydrograph was simulated for the 25-year storm event and the simulation predicts a sediment yield of 678,000 ft^3 (25,111 yd^3). This compares well with the estimated

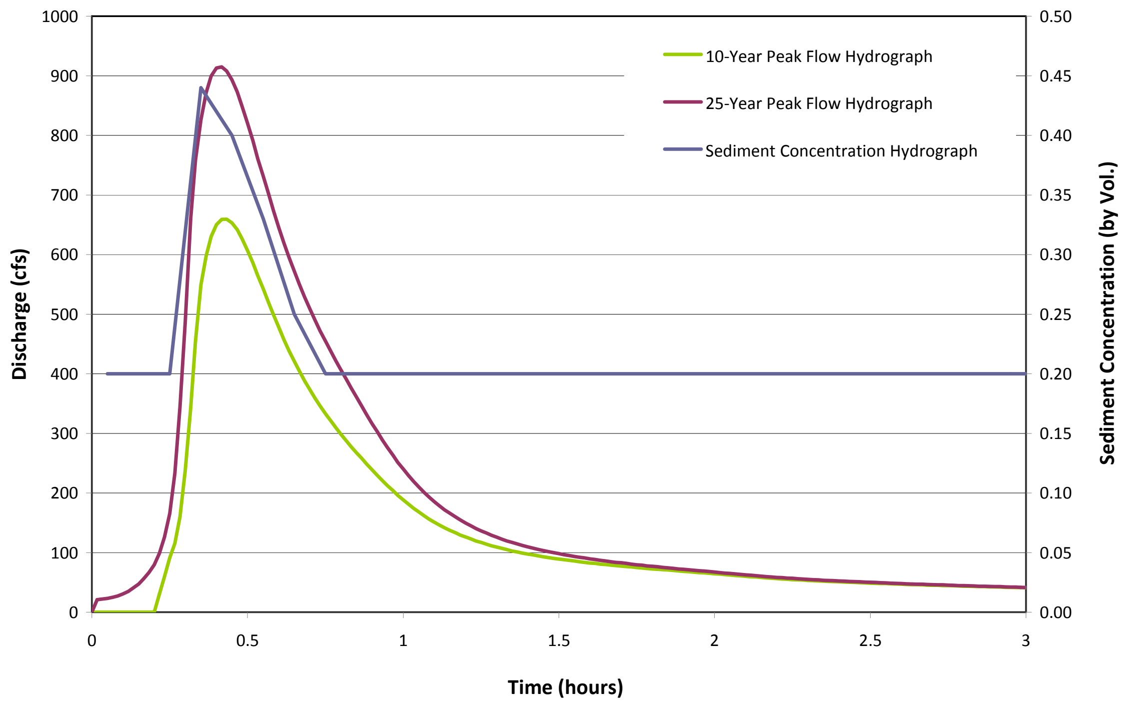

Figure 3.6. Sediment concentration hydrographs for the 10- and 25-year peak flow events.

volume of 680,000 ft^3 (25,185 yd^3) that occurred during the 1969 event (SLA and O'Brien, 1989a). SLA and O'Brien (1989a) predicted a sediment volume of 637,000 ft^3 (23,592 yd^3). The difference may be attributed to the difference in peak flow of the clear-water hydrograph. SLA and O'Brien (1989a) estimated a 25-year peak flow of approximately 700 cfs compared to 915 cfs (MEI, 2008) used in this study. As a result, Scenario 1 predicts a greater of volume of mudflow compared to the SLA and O'Brien (1989a) study.

3.2. Flood Hazard Index

A flood hazard index (FHI) was used to identify potential hazard areas for each of the three modeled scenarios. The FHI contains three hazard levels (High, Medium and Low) that were categorized based on event intensity of the mudflow using the Swiss Method (OFEE et al., 1997). A description of the danger to people and potential structural damage for each Hazard Level is defined in **Table 3.3**. The Swiss method defines the event intensity (EV) in terms of a combination of the sum of the maximum water depth (h) and the product of depth (h) and velocity (v) (**Table 3.4**):

$$EV = h + vh$$

where: h = flow depth
v = velocity

The Swiss method enables high intensities to be related in terms of depth independently of velocity. Delineation of the three intensity categories was conducted for the floodplain elements using the HAZARD module in the FLO-2D program and the output from the FLO-2D model. The FHI values were used to develop hazard maps for each of the mudflow simulations.

Table 3.3. Hazard Level descriptions (from FLO-2D guidelines on hazard maps, 2006).		
Mudflow Hazard Index	Map Color	Description
High	Red	People are in danger both inside and outside their houses. Buildings can be destroyed.
Medium	Orange	People are in danger outside their houses. Buildings may suffer damage and possible destruction depending on construction materials.
Low	Yellow	Danger to persons is low or non-existent. Buildings may suffer little damage, but flooding or sedimentation may affect building interiors.

Table 3.4. Event intensities for mudflows (modified from OFEE et al., 1997).			
Mudflow Hazard Index	Maximum Depth (h) (ft)	Logical Operator	Maximum Depth (h) times maximum velocity (v) (ft^2/s)
High	h >= 3.3	OR	vh >= 3.3
Medium	0.7 <= h <3.3	AND	0.7 <= vh <3.3
Low	0.7 <= h <3.3	AND	vh < 0.7

3.3. Flood Simulations

FLO-2D mudflow simulations were performed for the following scenarios:

1. 25-year peak flood event on Cornet Creek with the Townsend Street culvert blocked
2. 25-year peak flood event on Cornet Creek with all culverts and bridges blocked
3. 10-year peak flood along the east-side of the alluvial fan

Simulation 1 was performed assuming that mudflows are conveyed down Cornet Creek (along the flow path of the 1969 event) and the Townsend Street Culvert becomes blocked at the onset of flooding. The Townsend Street Culvert has relatively low conveyance capacity and there is low clearance between the thalweg of the channel and the bottom chord of the bridge. The low clearance of the bridge may allow large boulders to block the bridge at the onset of the mudflow and force more of the mudflow out of the channel and onto the alluvial fan.

Simulation 2 was performed assuming mudflows are conveyed down Cornet Creek and all of the culverts and bridges along Cornet Creek are blocked. This is considered a worst case scenario and was conducted to assess the maximum possible flooding over the alluvial fan at the 25-year flood event.

Simulation 3 was performed assuming the channel becomes blocked at the apex of the fan and flows avulse across the alluvial fan and are conveyed down the flow path of the 1914 event.

3.4. Model Results

The FLO-2D model was run for the three scenarios, and the results were used to map and evaluate the extent, depth, velocity, and hazard potential.

3.4.1. Scenario 1

The model results for Scenario 1 show extensive mudflow inundation in a northeast to southwest direction from the apex of the fan, through the western part of the town to the San Miguel River (**Figure 3.7**). The flood inundation extends from the western boundary of the model, easterly, to approximately Townsend Street. The total predicted area of inundation is approximately 36.2 acres.

The simulated blockage at Townsend Street Bridge forces the flow from the channel into the overbank and flow is rapidly conveyed down Townsend Street towards the San Miguel River (Figure 3.7). Flows that break out of channel in the vicinity of West Columbia Avenue and North Davis Street are conveyed down the historic flow path of Cornet Creek. Cornet Creek was realigned to the east of the historic flow path following the 1969 event in order to shorten the flow path to the San Miguel River.

The depth of flooding in the channel is approximately 15 feet near the apex of the fan and the channel depths range from 4 to 7 feet in the lower section of Cornet Creek. The depth of overbank flooding ranges from 4 to 7 feet near the apex of the fan to very shallow depths at the margins of the flooding. The majority of the flooding throughout the Town is less than 0.5 feet; however, there are higher depths at topographically low points, such as along the historic flow path of Cornet Creek.

The maximum flow velocities occur within the Cornet Creek channel and channel velocities range from 6 to 15 fps (**Figure 3.8**). Relatively high velocities are predicted along the streets, particularly in the north-south direction where flows are conveyed downhill at velocities up to 7 fps and in the east-west direction along Columbia Avenue where velocities Reach 13 fps was flows break out from the main channel. Generally, the velocities in the street are higher than in the overbank areas due to their lower roughness values and confinement by the street curbs. Maximum flow velocities in the overbank areas range from approximately 0.5 to 5 fps. The majority of the overbank flow velocities range between 1 and 2 fps, which is equivalent to a slow walking speed and is consistent with observed velocities for mudflows.

The hazard potential mapping shows that the majority of the high and moderate hazard potential areas are located within- and adjacent to Cornet Creek upstream of the Colorado Avenue crossing, as well as along the historic, pre-1969 realignment flow path (**Figure 3.9**). The majority of the High hazard areas are located near the apex of the fan and along the alignment of the historic channel flow path. Similarly, the Moderate hazard potential areas are mostly aligned with the existing and historic flows paths. The Low hazard potential areas are mostly located at the margins of the higher hazard potential areas. The hazard potential mapping indicates that approximately 4.4, 14.7 and 15.0 acres are classified as High, Moderate and Low hazard potential areas, respectively (**Table 3.5**).

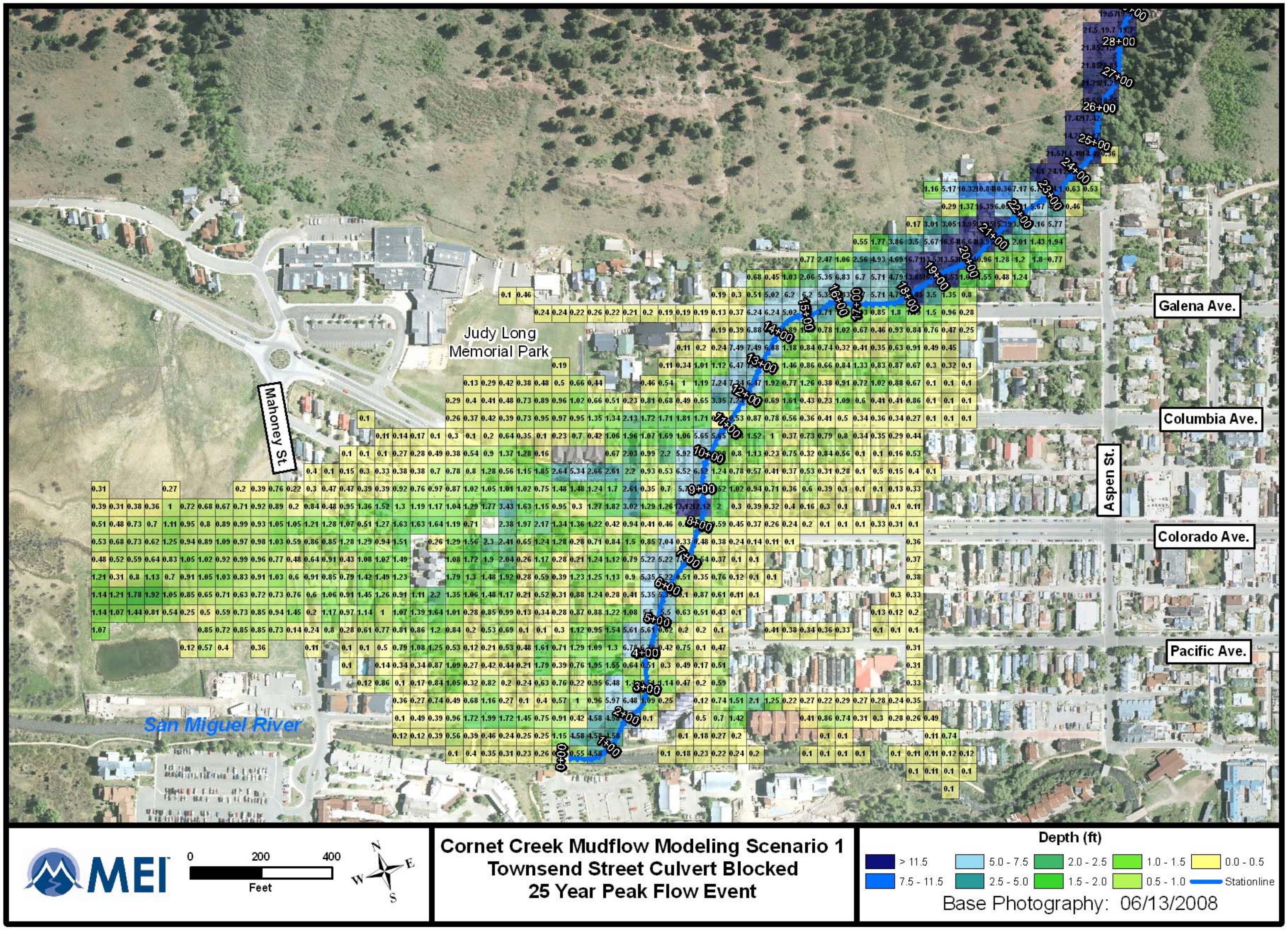

Figure 3.7. Predicted maximum inundation depths for Scenario 1 (25-year peak flow event with the Townsend Street Culvert blocked).

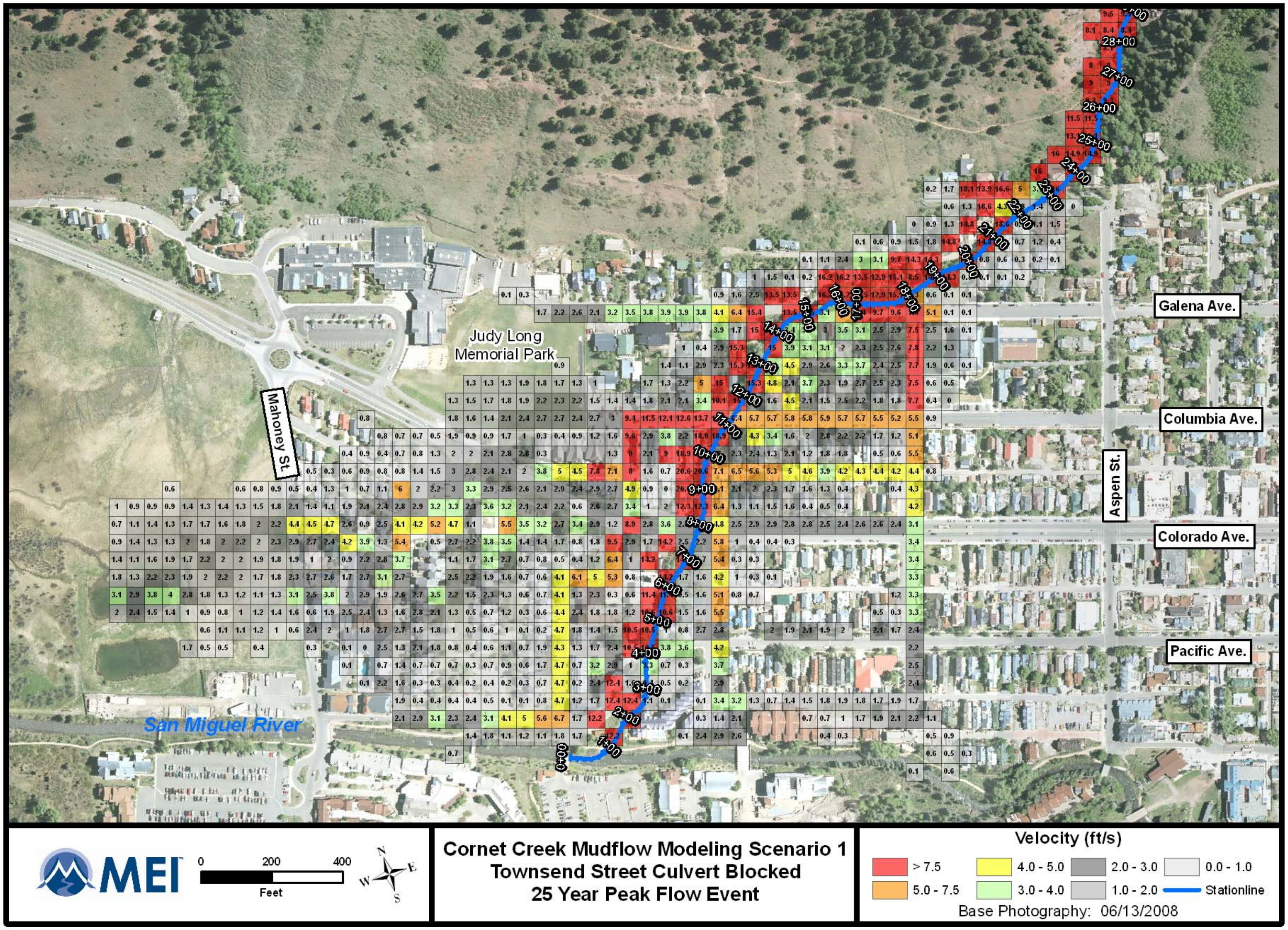

Figure 3.8. Predicted maximum velocities for Scenario 1 (25-year peak flow event with the Townsend Street Culvert blocked).

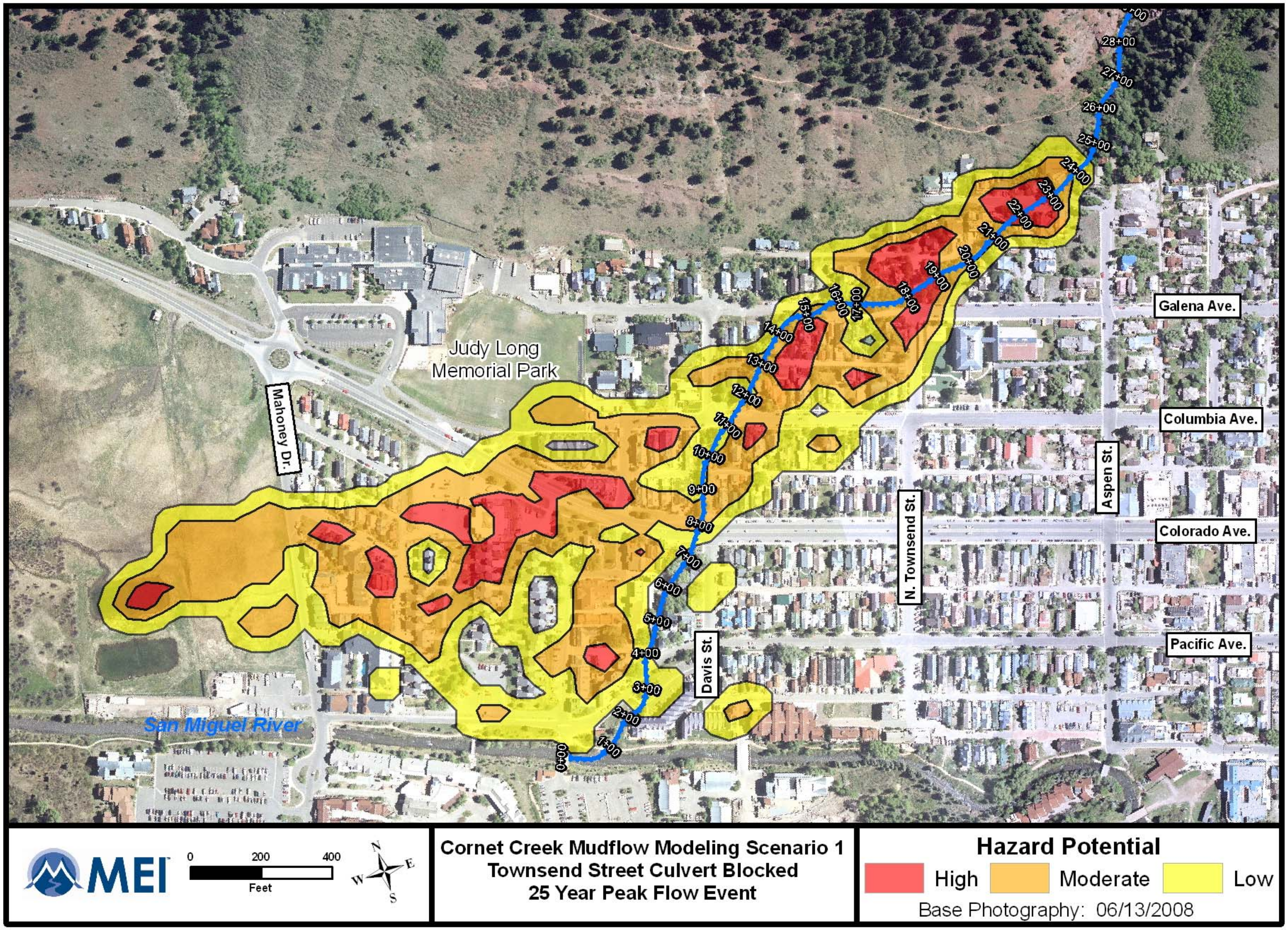

Figure 3.9. Predicted Hazard Potential for Scenario 1 (25-year peak flow event with the Townsend Street Culvert blocked).

Table 3.5. Summary of area (acres) of Low, Moderate and High Hazard potential for Scenarios 1, 2, and 3.			
Hazard Potential	Scenario		
	1	2	3
Low	15.0	15.3	14.6
Moderate	14.7	20.0	16.0
High	4.4	13.6	19.5
Total	34.1	49.0	50.0

A comparison of the extent of inundation between Scenario 1 and the 1969 mudflow event shows that Scenario 1 closely follows the 1969 flow path (**Figure 3.10**). The predicted extent of the inundation for Scenario 1 is approximately 150 feet wider near the head of the fan than observed during the 1969 flood. The most notable difference between the two events is that the predicted flooding under Scenario 1 extends farther downstream beyond the 1969 flooding to the San Miguel River, the result of realignment and channelization of Cornet Creek following the 1969 event. Flooding also extends farther west along the historic flow path which may be due to the increase in the number of buildings, the increase in size and number of paved streets, and the increased conveyance capacity of Cornet Creek compared to 1969 conditions. The increase in the number and size of the buildings reduces the storage capacity, blocks flows and reduces the flow conveyance area within town. The reduced conveyance area reduces the depositional area and forces flows farther along the flow path, while the increased conveyance in Cornet Creek transports a greater volume of material downstream (Figure 3.10).

3.4.2. Scenario 2

The model results for Scenario 2 show similar flooding trends to those for Scenario 1 for the inundated areas to the east of Cornet Creek. The simulated blockage of all the bridges and culverts creates additional inundation in the area to the west of the channel, particularly in the vicinity of Judy Long Memorial Park and in the open field located west of Mahoney Drive. The maximum predicted channel depths are slightly higher than those predicted in Scenario 1 due to the simulated blocking of the culverts and bridges (**Figure 3.11**). The maximum channel depths range from 4 to 9 feet throughout the majority of the channel. The predicted total area of inundation for Scenario 2 is 45.3 acres. Similarly, the maximum floodplain depths are slightly higher in Scenario 2 than in Scenario 1 due to the increased overbank flooding resulting from the blocked structures. The overbank depths range from 0.1 to 7 feet with the majority of depths being less than 0.5 feet.

The maximum flow velocities in the channel range from 6 to 15 fps (**Figure 3.12**). Overbank velocities are similar to Scenario 1 with values ranging from 0.5 to 5 fps, with the majority of the maximum overbank flow velocities ranging between 1 and 2 fps.

The hazard potential mapping (**Figure 3.13**) shows an increase in hazard potential, especially in the area located to the west of Cornet Creek along the former course. In the area located southwest of the intersection of West Colorado Avenue and South Tomboy Street, there are significantly more High hazard potential areas than predicted in Scenario 1. The hazard potential mapping indicates that approximately 13.6, 20.0 and 15.3 acres are classified as High-, Moderate- and Low-hazard potential areas, respectively (Table 3.4).

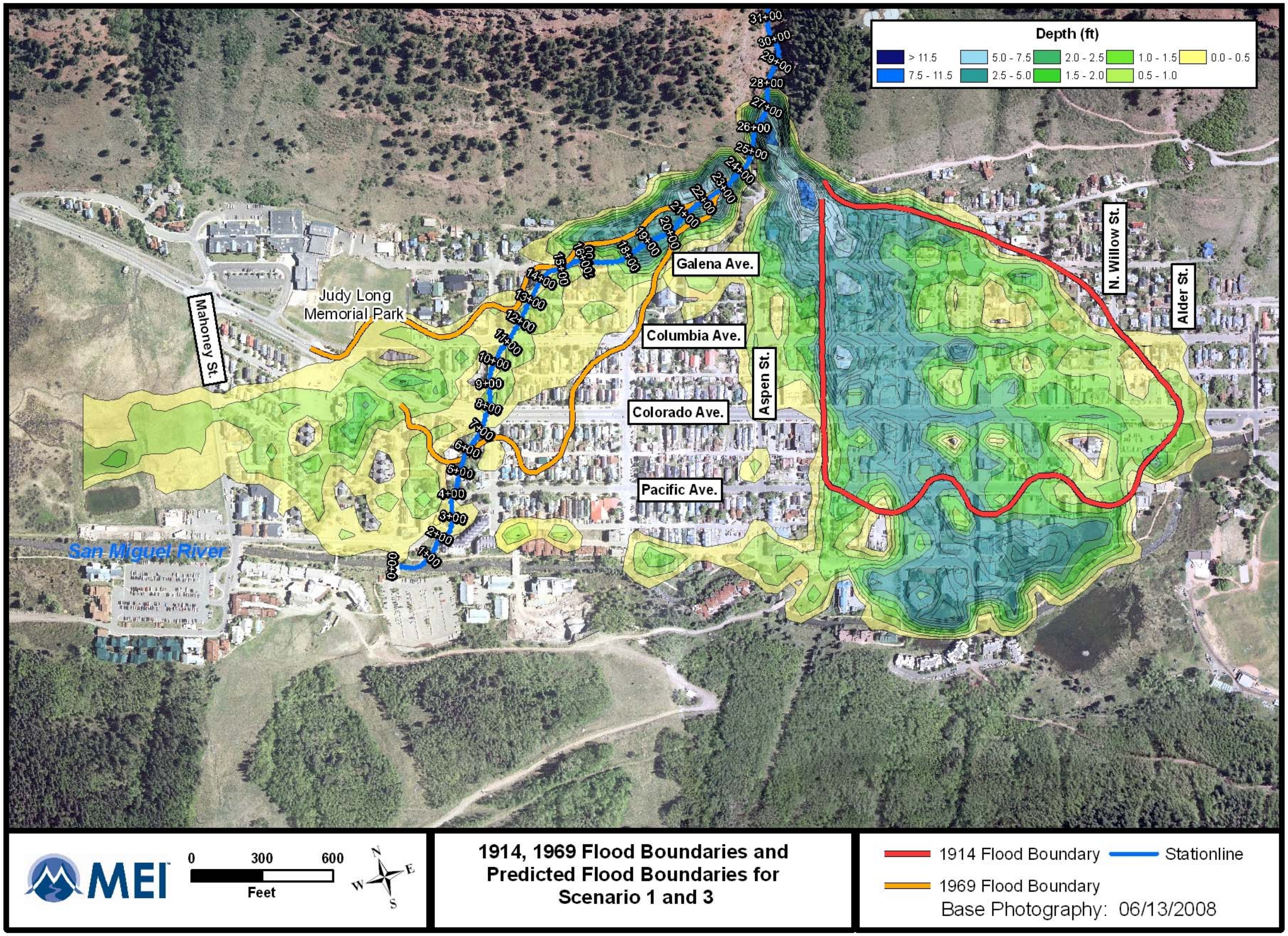

Figure 3.10. Comparison the extent of flooding between Scenarios 1 and 3 with the 1914 and 1969 mudflow events.

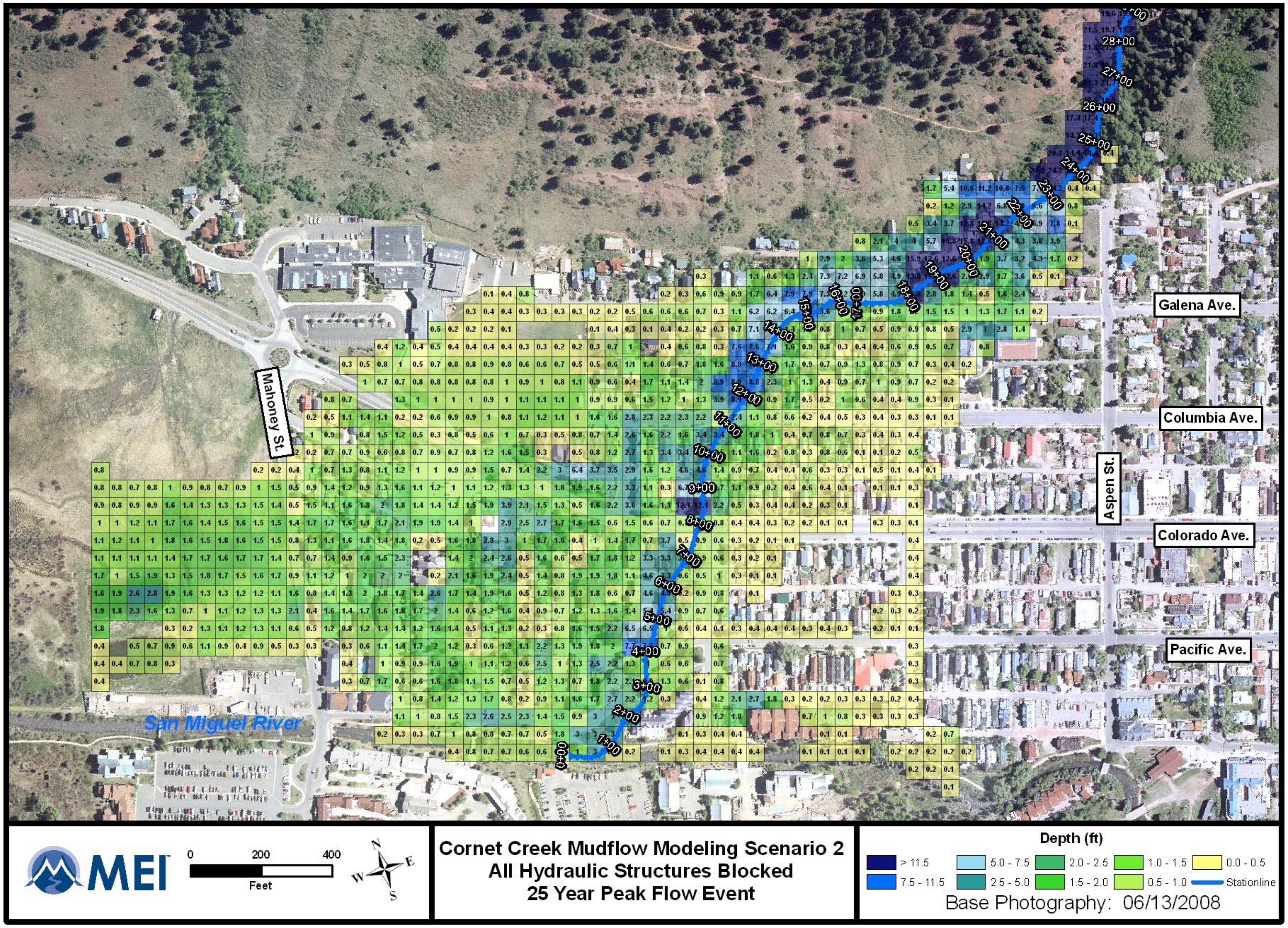

Figure 3.11. Predicted maximum inundation depths for Scenario 2 (25-year peak flow event with all bridges and culverts blocked).

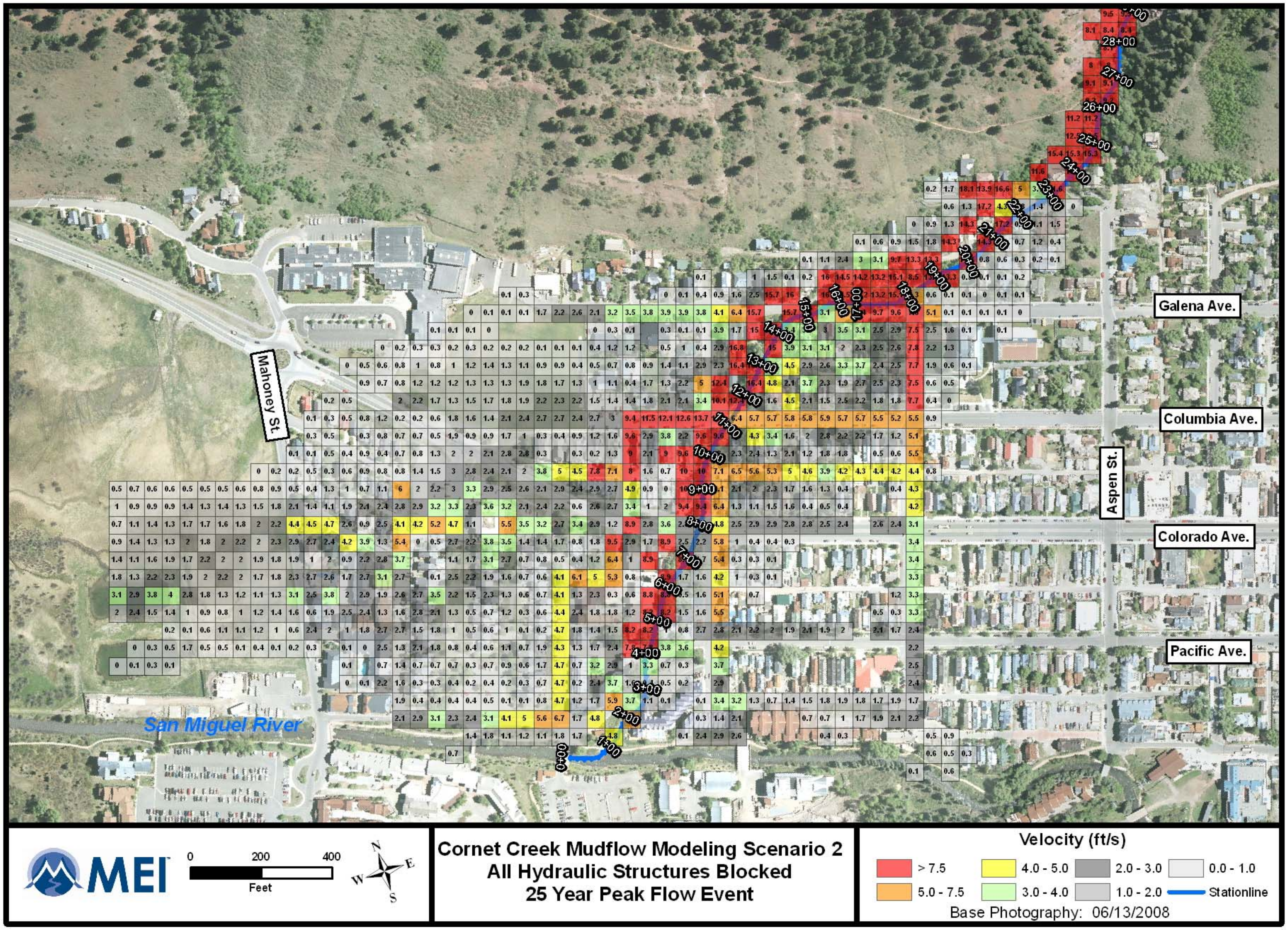

Figure 3.12. Predicted maximum velocities for Scenario 2 (25-year peak flow event with all bridges and culverts blocked).

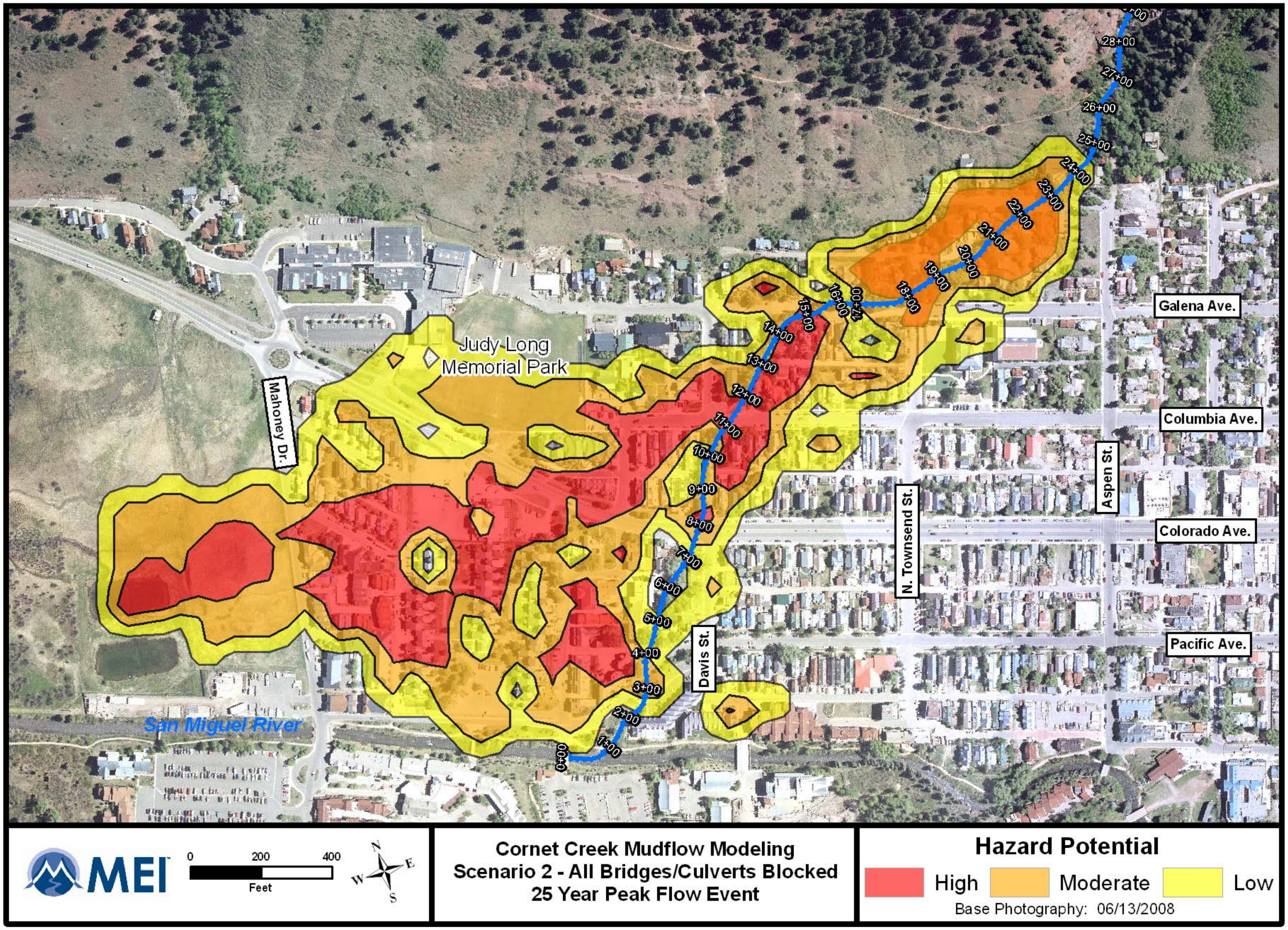

Figure 3.13. Predicted Hazard Potential for Scenario 2 (25-year peak flow event with all bridges and culverts blocked).

3.4.3. Scenario 3

The model results for Scenario 3 show that the flooding directly follows the flow path of the 1914 flood (Figure 3.10) and the flood inundates the majority of the eastern side of the alluvial fan (**Figure 3.14**). The flow path follows the topographic depression along the path of the 1914 flood that extends in a southerly direction from the head of the fan, through the main business district to the San Miguel River.

The depths of flooding are greatest near the apex of the fan with depths ranging from 8 to 15 feet. The flow depths along main flow path range from 1 to 8 feet deep with the majority of flow depths on the order of 3 feet. Flow depths towards the margins of the flooding typically range from 1 to 2 feet. Flow depth on the streets are approximately 0.1 to 1.5 feet to the west of the main flow path, and are approximately 0.5 to 3 feet to the east of the main flow path. The predicted total area of inundation for Scenario 3 is 67.8 acres. The streets play a major role in conveying flows in an east-west direction as shown by the street inundation depths, particularly along the western margin of the flooding. In general, the inundation depths for Scenario 3 are higher than those predicted by Scenarios 1 and 2. In Scenarios 1 and 2, sediment in stored within the channel, particularly near the apex of the alluvial fan. In Scenario 3, there is little channel storage capacity because flows are forced from the main channel, and therefore, more sediment is deposited on the alluvial fan creating greater depths of deposition.

The maximum flow velocities in the channel range from 6 to 15 fps (**Figure 3.15**). The overbank velocities in the vicinity of the flow break-out from the main channel are approximately 5 to 7 fps. In general, the velocities are highest along the streets, especially in the north-south direction, where maximum velocities up to 5 fps occur. The velocities on the floodplain elements (i.e. not the streets) generally range from 0.1 to 2 feet fps, with the higher velocities occurring along the center of the flow path.

The hazard potential mapping shows a significant band of High hazard potential that extends along the main flow path of the 1914 flood from the apex of the fan to the San Miguel River (**Figure 3.16**). The hazard potential decreases to the east of the main flow path. The hazard potential mapping indicates that approximately 14.6, 16.0 and 19.5 acres are classified as High, Moderate and Low hazard potential areas, respectively (Table 3.4).

Although the 1914 conditions were not intended to be simulated, a comparison of the extent of inundation between Scenario 3 and the 1914 mudflow event indicates that extents of inundation are similar (Figure 3.10), particularly along the eastern margin of the flooding. The flow breakout area at the head of the fan is in a different location in Scenario 3 compared to the 1914 event. As a result, the area of inundation extends farther west to Aspen Street in Scenario 3, whereas, the western extent was located at Oak Street during the 1914 event. In addition, Scenario 3 predicts that the flooding extends to the San Miguel River, whereas the 1914 mudflow stopped approximately 500 feet short of the river (SLA and O'Brien, 1989a).

3.5. Summary

The results of the FLO-2D modeling clearly show that there is a mudflow (debris flow) hazard on the Cornet Creek fan. Areas of highest predicted flow depth, velocity, and hazard potential are associated with the flow paths of the historic mudflow events in 1914 and 1969, which in turn are controlled by the topography of the alluvial fan. In general, the flow depths are highest near the fan apex and along the channel of Cornet Creek, and they diminish in the downstream direction and away from the channel. Non-channel velocities are highest in the streets, especially those that have a general north-south orientation, and range from 5 to 10 fps. In the non-channel overbank areas, velocities are relatively slow and range from 1 to 2 fps.

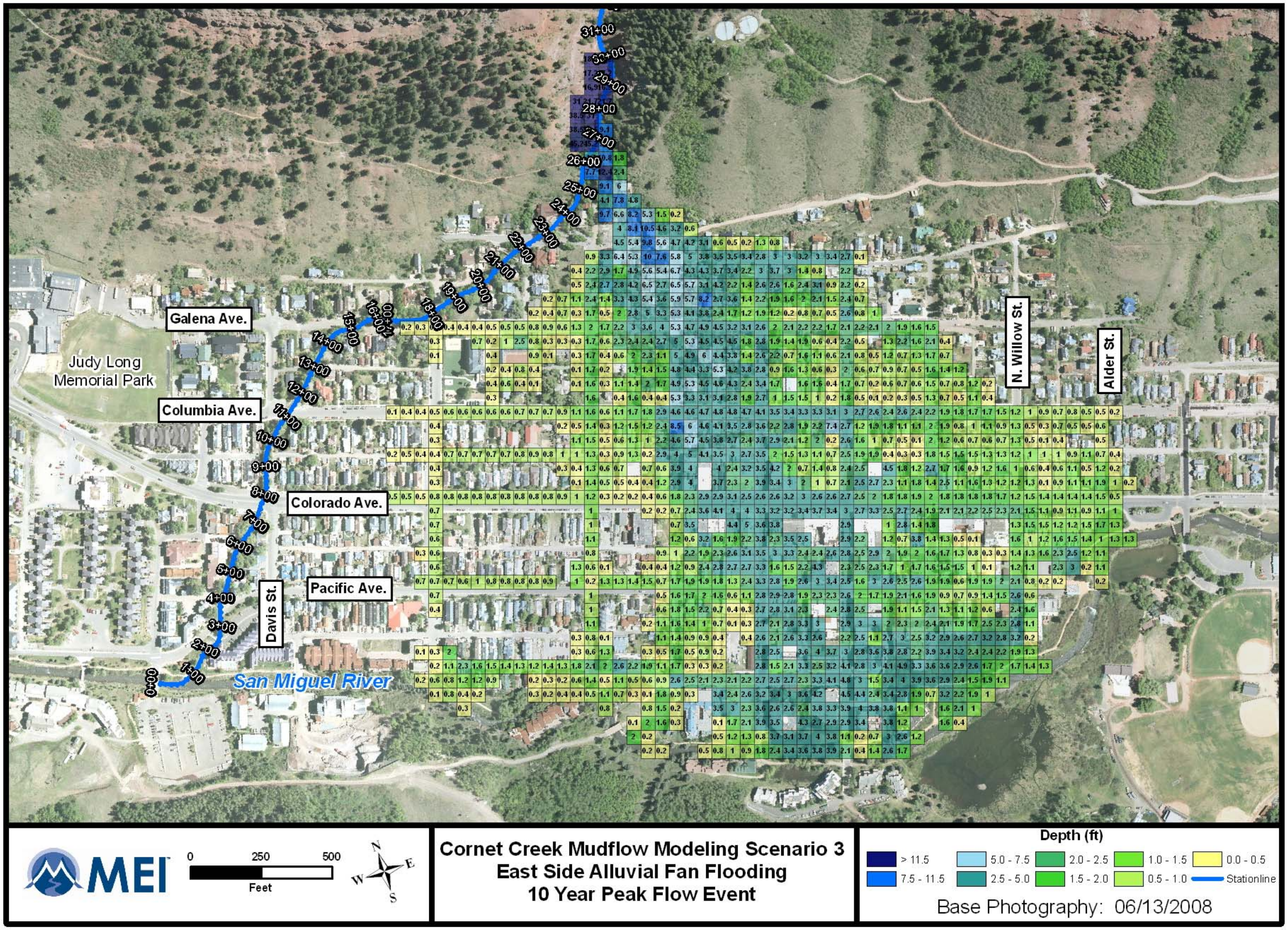

Figure 3.14. Predicted maximum inundation depths for Scenario 3 (10-year peak flow event along the east side of the alluvial fan).

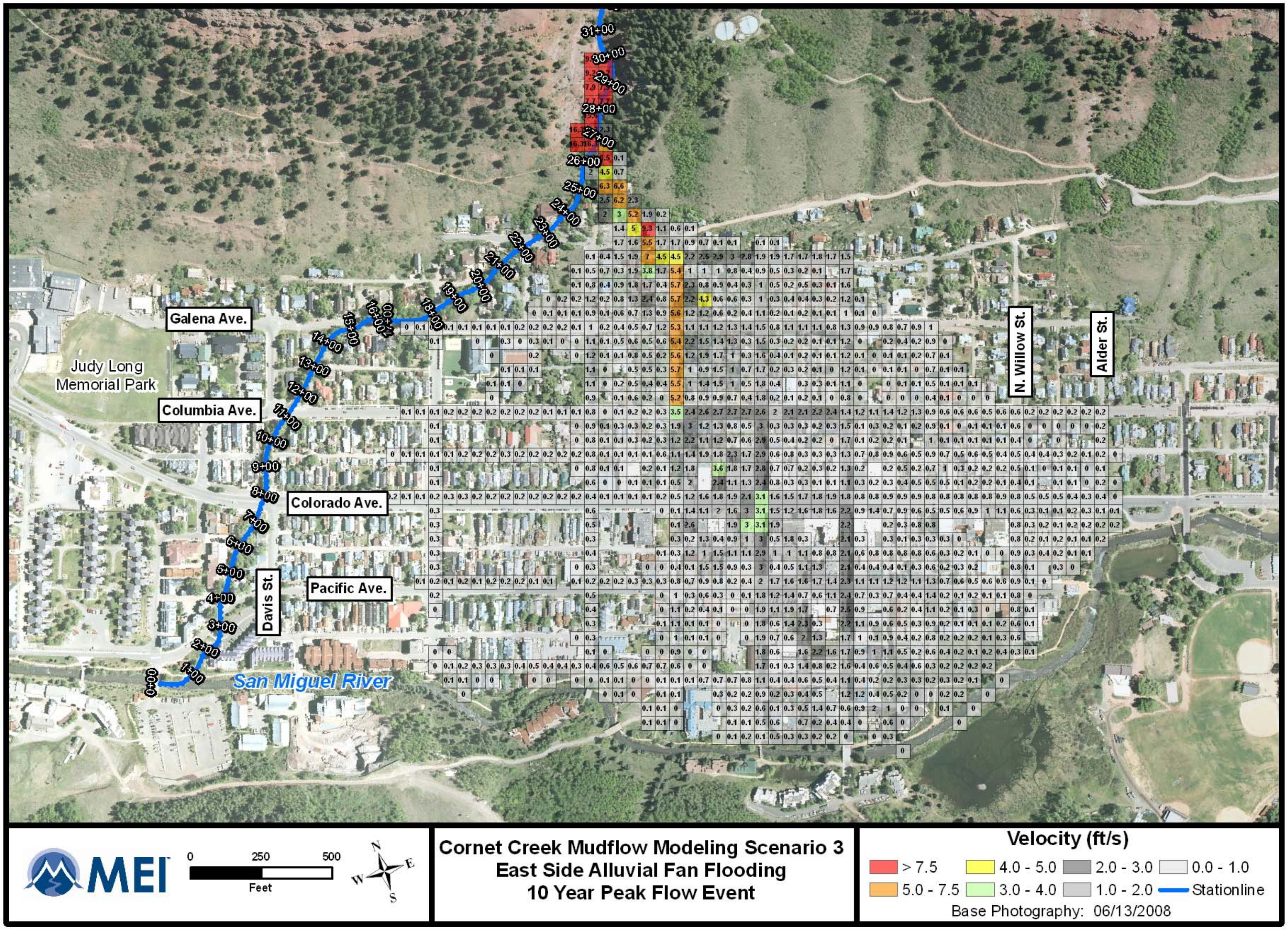

Figure 3.15. Predicted maximum velocities for Scenario 3 (10-year peak flow event along the east side of the alluvial fan).

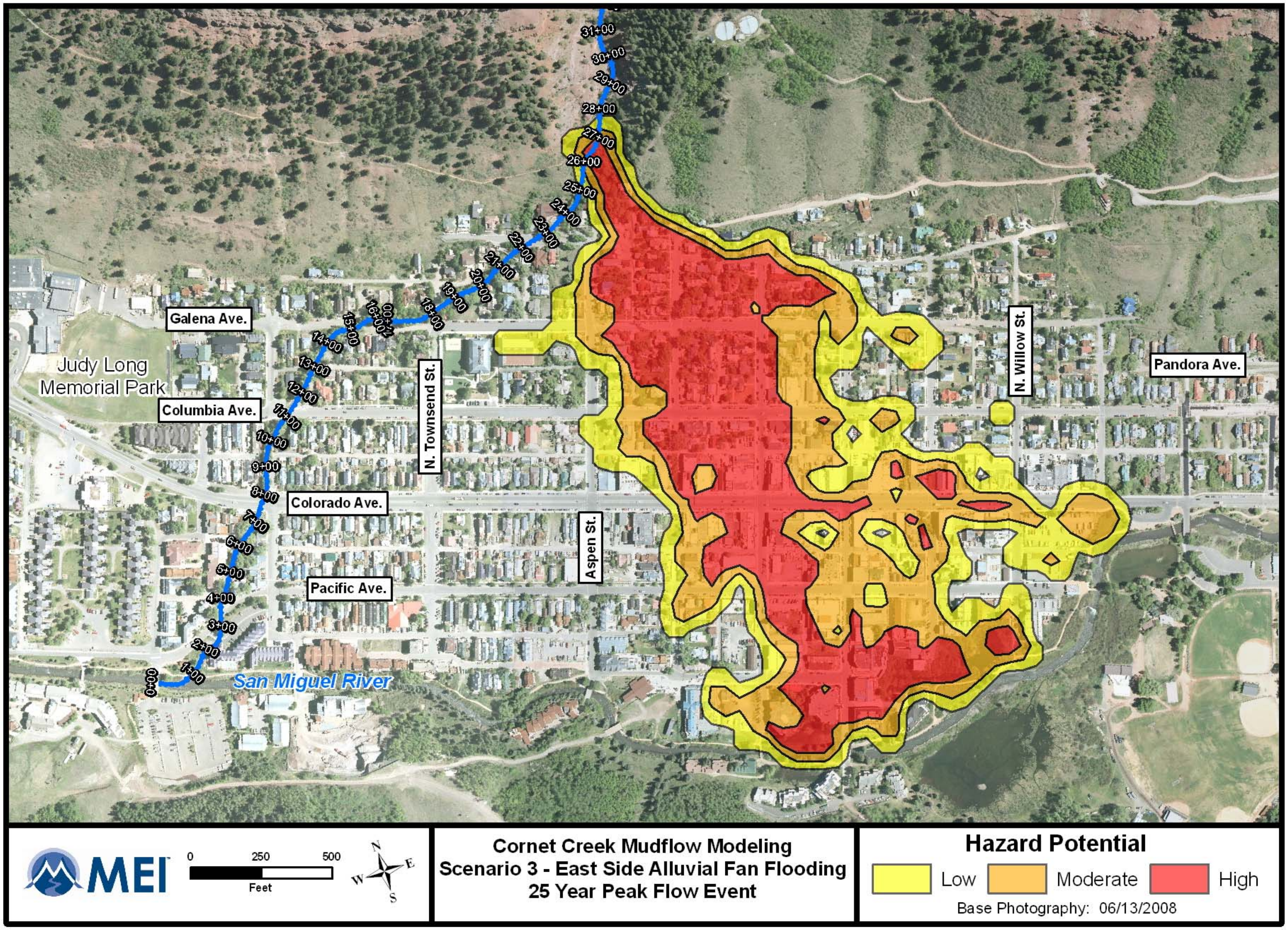

Figure 3.16. Predicted Hazard Potential for Scenario 3 (10-year peak flow event along the east side of the alluvial fan).

4. DEBRIS FLOW PREDICTION, WARNING, AND MITIGATION

The Town of Telluride is situated directly on a composite alluvial fan (NRC, 1996) created both by alluvial sedimentation as well as debris flows (mudflows) from the Cornet Creek watershed. Less frequent, but more damaging debris flows have occurred twice (1914 and 1969) in the last approximately 100 years (**Figures 4.1 and 4.2**). An assessment of the risk from debris flows based on the historical behavior of the system (about 2 percent each year) is essential in the process of evaluating management and mitigation options (MEI, 2008). However, the probability of occurrence of a debris flow is not an independent, random event in the same way that runoff floods are assumed to be (NRC, 1996). Debris accumulates in source localities and along stream channels over timescales from decades to centuries between events that evacuate the debris in the form of debris flows (Benda and Dunne, 1987; Dunne, 1991; Reneau and Dietrich, 1991). Consequently, the probability of the occurrence of a significant debris flow is conditional on the accumulation of transportable debris within the basin, antecedent soil moisture conditions and high intensity precipitation.

Although the general perception in the community may be that the risk is relatively low given that the last significant debris flow (mudflows) occurred 40 years ago in 1969, development within the Town has increased the risk of damage should an event occur. For example, additional development on the Cornet Creek fan and encroachment of the channel of Cornet Creek have increased the potential for damage, and the limited capacity of the channel further reduces the chance that flows will remain within the confines of the creek (MEI, 2008). Risk analysis is the process used to identify and compare the benefits and damages from a particular threat (Greminger, 2003). Therefore, even if large events such as the 1969 debris flow are less likely to occur, relatively small events such as the July 2007 flood that distributed a significant amount of sediment to a small portion of the Town near the apex of the Cornet Creek fan can still cause a significant amount of damage and thus be considered a significant risk (**Figure 4.3**).

Management of these risks requires an understanding of the potential magnitude, frequency and associated impacts of a given threat. It also requires an understanding of the viability of possible prediction and mitigation techniques based on constraints such as budgets and public opinion. Based on the results from the FLO-2D modeling of the Cornet Creek fan (Chapter 3) widespread inundation by debris-flow material is likely to occur throughout the Town, even during less intense, more frequent storm events. As a result, a variety of techniques to manage the risk to life and property need to be considered. These may include structural and non-structural control measures and early-warning systems. In general, the following, individually or in various combinations, have been identified as management measures (countermeasures) against debris flows:

1. Hazard Impact Assessments
2. Advance (early) Warning Systems
3. Event (real-time) Warning Systems
4. Structural Mitigation Measures

Figure 4.1. Historic photograph taken within Town of Telluride showing debris and damage caused by 1914 debris flow event.

Figure 4.2. Historic photograph taken within Town of Telluride showing debris and damage caused by 1969 debris flow event.

Figure 4.3. Looking west along Dakota Avenue at sediment deposited during July 2007 flood on Cornet Creek.

4.1. Hazard Impact Assessments

A key component of any hazard mitigation decision support system is an initial evaluation to identify the portions of an area or community that might be directly threatened by a particular hazard. In the case of debris flows from the Cornet Creek Basin, the mapping of debris flow run-out areas on the fan, which is discussed in detail in Chapter 3 of this report, provides critical information to help community leaders make informed decisions regarding mitigation options. Under ideal conditions, managing the risks of natural hazards can include land-use planning, development of early-warning systems, installation of protective structures, and development of protocols to deal with disasters as well as to restore normal conditions after natural disasters (Greminger, 2003). Unfortunately, given the amount of development on the Cornet Creek alluvial fan and its close proximity to the channel, the process of land-use planning to help manage the risks from debris flows is somewhat moot (**Figure 4.4**). However, the inundation mapping developed and described in this report can be used to identify items such as homes, structures, utilities, and road crossings that are located within areas of higher-risk. This information can be used to develop hazard mitigation protocols such as the delineation of safety zones, and the development of warning systems, as well as evacuation, rescue, and repair plans (Wei et al., 2008; Petrascheck and Kienholz, 2003). Hazard mapping based on FLO-2D model output for debris flows on highly urbanized alluvial fans in Venezuela has been officially adopted in that country for designing emergency plans and new land-use policies (Garcia et al., 2003).

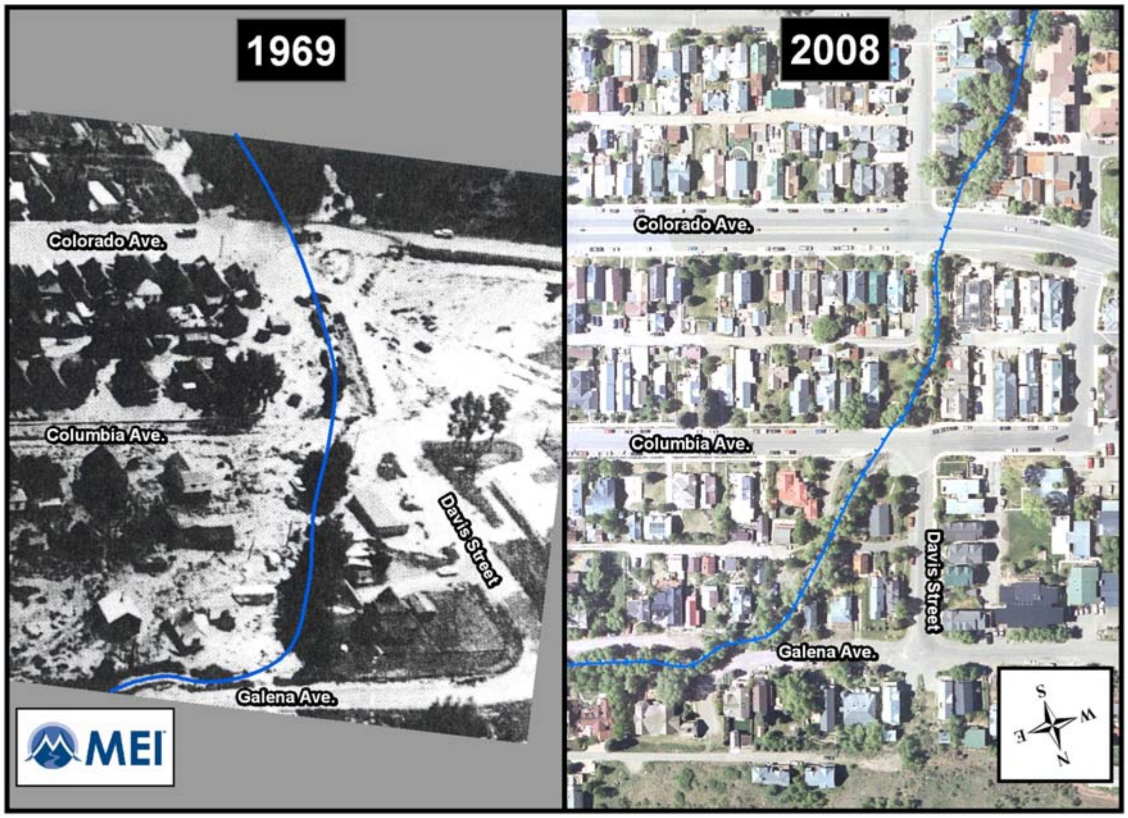

Figure 4.4. Aerial photographs of a segment of Cornet Creek between Galena Avenue and Colorado Avenue showing mudflow inundation during the 1969 flood as well as the subsequent development and encroachment of the channel during the last 40 years.

4.2. Advance (early) Warning Systems

Advance or Early-warning systems have generally consisted of identification of precipitation intensity-duration thresholds and real-time rainfall measurements. Historically, these have been the basis for landslide warning systems, but have also been applied towards the prediction of debris flows that frequently result from the landslides (USGS-NOAA, 2005; Chang, 2003; Arattano and Marchi, 2008). The primary purpose of these systems is to provide sufficient time to prepare for an oncoming threat, which makes them most applicable to residential areas where there is a high potential for loss of life. The primary disadvantage of most early-warning systems is that the forecast accuracy is limited, resulting in a high potential for false alarms (MEI, 2008).

A warning threshold can consist of both a minimum or maximum level of some variable for a particular process, such as a debris flow, to occur. Typically, a minimum threshold defines the lowest level below which a process does not occur, and a maximum threshold defines the level above which a process always occurs. Assuming that the required data can be collected and monitored, debris-flow thresholds described as 'process-based' require not only rainfall data, but also information on identification and characterization of specific debris source areas, soil type, moisture conditions, and pore-water pressures. Unfortunately, process-based information is not commonly available and is often very costly to obtain (Guzzetti et al., 2007; USGS-NOAA, 2005).

Empirically based threshold models also exist, which utilize measured data that correlate rainfall conditions to actual slides that have previously occurred. The sensors most commonly adopted for use in these systems are those normally used for hydrometeorological monitoring and typically consist of telemetered networks of rain gauges and weather radar (Arattano and Marchi, 2008). Again, the lack of any existing precipitation records, measuring devices, and documented correlations to localized slide events in the Cornet Creek watershed, limits the full potential of this method. However, it may be possible to develop an early-warning system that utilizes an empirical threshold based on measured data from nearby precipitation gages or weather radar records in conjunction with documented events that have historically impacted the Town or other locations within the Upper San Miguel River valley. In addition, the development of a threshold precipitation value that represents not a maximum level, but a level at which a debris flow is ‘likely’ to occur, may be a reasonable approach to consider.

An advance warning system threshold can be represented as a critical rainfall line on a plot of rainfall intensity versus time, which could also include a more conservative limit as a foundation for the issuance of warnings (**Figure 4.5**). Critical rainfall thresholds could be identified on the basis of historic rainfall and weather radar records which correspond to conditions that have triggered debris flows. Variables other than average rainfall intensity may also prove more useful, and thresholds could be further refined by accounting for antecedent precipitation, which influences soil saturation (Arattano and Marchi, 2008; Takahashi, 2007). Even in the absence of recorded data, the threshold concept is applicable, and if necessary, could be simplified to a general rule based on the interpretation of a storm’s magnitude. In any case, the key issue pertaining to the enhancement of public safety is to actively monitor storms, either quantitatively or qualitatively, in order to estimate the potential threat from a flood or debris-flow event. Debris-flow events originating from the Cornet Creek Basin have historically occurred in the period from late July to early August, therefore monitoring of hydrometerological conditions should be heightened in the July-August period when event-triggering local thunderstorms are most likely to occur.

4.3. Event (real-time) Warning Systems

Event-triggered, real-time warning systems provide another type of non-structural countermeasure against debris flows. These warning systems are designed to detect debris flows while in progress. Although they have a much smaller lead time than early-warning systems, they are much less prone to false alarms (Arattano and Marchi, 2008). The primary advantage of real-time warning systems is that they can be linked to lights, electronic signs, sirens, and barriers to help facilitate emergency evacuations, and closures of roads as well as vehicle and pedestrian crossings to prevent or reduce potential damage or loss of life (Huebl and Fiebiger, 2005; MEI, 2008).

Real-time event-warning systems require the use of a variety of sensors that can provide immediate notification of an impending emergency. Numerous different types of sensors have been evaluated and implemented to aid in the detection of debris flows, and **Table 4.1** provides a summary of the principal sensors that have been used in event-triggered warning systems.

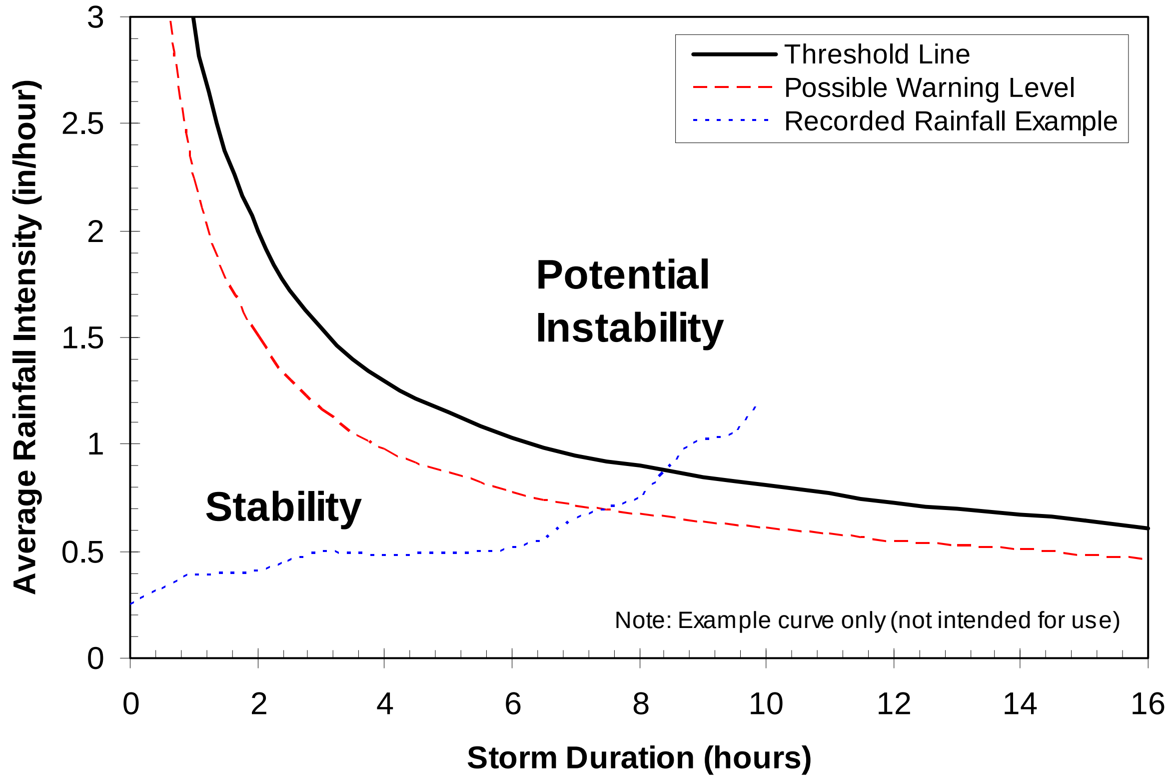

Figure 4.5. Example plot of critical rainfall threshold for debris-flow initiation.

In addition to the sensors themselves, a complete real-time warning system must include components such as data acquisition and processing units as well as the devices that will actually spread the alarm. As a result, not only is the selection of an appropriate sensor important, but the selection of an appropriate connection system (i.e., physical cable connection or wireless system) is also necessary (Arattano and Marchi, 2008). Obviously, the rugged terrain within the Cornet Creek Basin may limit the ability to connect sensors and processing units with cable, but that same terrain may also cause interference with wireless systems. A site-specific investigation of the viability of the two options would likely be necessary.

Appropriate connection systems are also largely dependent on where in the basin the sensors would need to be installed. Installation of sensors near the mouth of the canyon may be easier, but since the amount of warning time is critical, it may be more appropriate to install sensors farther upstream in the basin in order to increase the warning time. To reduce false alarms, installation of sensors as a small series along the creek, as a complete network, or as an integrated system (i.e., network of multiple types of sensors), has demonstrated improved results. Additionally, given the considerable amount of recreation that occurs within the Cornet Creek Basin, careful placement of sensors in locations that are less prone to human interference is likely to be necessary.

Table 4.1. Summary of principal sensors used for real-time warning systems of debris-flow events (Arattano and Marchi, 2008; Itakura et al., 2005).			
Sensor	Operation	Advantages	Disadvantages
Ultrasonic, Radar, and Laser Sensors	Electronic measurement of the flow stage by focusing downward on the channel from above	Easy to set warning thresholds. Non-contact detector (i.e., no restoration required after activation)	Ultrasonic sensors often have to be hung over the channel; installation can prove difficult if channel banks are unstable; more prone to damage
Geophones and seismometers	Measurements of ground vibrations caused by debris flow	Easy and safe installation (sensors are buried in safe locations along stream banks)	Setting warning thresholds can be quite complicated. Risk of false alarms due to other sources of ground vibration
Pendulums	Detection of the debris flow from the tilting of the pendulum	Simple and robust device. Contacts debris flow, but may not require much restoration after activation	Pendulum must be hung over the channel; installation can prove difficult if channel banks are unstable. Risk of false alarms (e.g. falling trees, passage of animals)
Wire Sensors	Detection of debris flow from wire breaking	Simple and robust device	Need for restoration after activation. Risk of false alarms (e.g., falling trees, passage of animals)
Photocells (e.g., Infrared Photobeams)	Detection of debris flow by interruption of beam emitted by sensors	Non-contact detector (i.e., no restoration required after activation)	Careful installation is needed to avoid having sensors come into contact with the flow
Charge-coupled device (CCD) camera for machine-vision detection	Recognition of debris flows through conversion of optical data into electronic signal	Safe installation (camera can be placed outside of channel)	Presence of fog or occurrence of debris flow at night may complicate use of system

All of the sensors summarized in Table 4.1 are installed at a stationary point along the creek. However, at the time of writing this report, one additional sensor type was identified that is not yet on the market but has undergone recent testing. The sensor is described as both a wireless mobile sensor and a geotechnical mass flow sensor that is placed within the channel and moves with the debris flow along its path. The sensor consists of a pyramid-shaped, weather-proof housing that contains a motion sensor, GPS unit, radio transceiver, logic unit, and solar cell connected to a battery (**Figure 4.6**). The sensors are intended to be placed in the channel but above the level of normal stream flow so that when a debris flow makes contact and displaces the unit, the motion triggers the sensor to send out an alert. In general, these units are designed to work as a network of multiple sensors spread out longitudinally along the channel so that only multiple displacements will trigger the alarm system, thus reducing the potential for false alarms. The primary benefit of the system is that installation costs are reduced, and the sensors themselves are said to be low cost, which allows them to be readily and cheaply constructed and maintained. Apparently, the sensors can also be camouflaged in a variety of

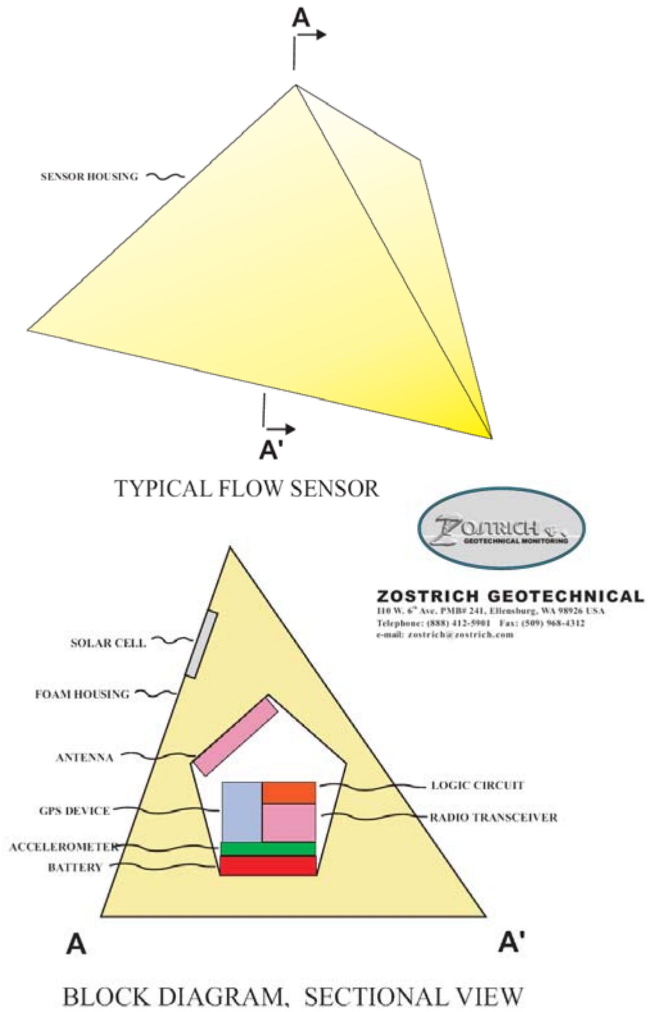

Figure 4.6. Schematic of geotechnical mass flow sensor (Image based on promotional information obtained from Zostrich Geotechnical Monitoring).

ways to avoid being noticed by the public (Cho et al., 2008; Richard Mathis, Zostrich Geotechnical, personal communication, March 2008).

All of the real-time warning systems described in this section have potential challenges associated with installation, maintenance, cost, or even false alarms, and may not provide much of an advance warning given the high velocity of typical debris flows. However, as a risk mitigation tool, even if the systems can only provide notice on the order of a few minutes, it may be enough to reduce or eliminate loss of life during these events.

4.4. Structural Mitigation Measures

Development of hazard assessments and warning systems are integral parts of a mitigation plan, but none of these techniques are capable of providing a physical means with which to reduce or eliminate potential threats. Common techniques used to mitigate debris flows include construction of conveyance channels (e.g., the debris conveyance flumes in the Town of Ouray), diversions, catchment basins, and debris-trapping structures. Given the current state of development on the Cornet Creek fan, construction of a debris conveyance flume, diversion structure, or a catchment basin is not feasible. Therefore, the most viable option is to construct a debris-trapping structure such as a debris-flow check dam (sabo dam) (MEI, 2008; Takahashi, 2007).

A variety of debris-trapping structures have been used worldwide, but concrete check dams have been the most commonly used types of structures. However, rather than building a solid structure that will retain all sediment in the channel, open-type or slit-type check dams have been used to allow some sediment bypass under normal conditions while maintaining the ability to retain larger material associated with a flood or debris-flow event (MEI, 2008). Open-type check dams primarily consist of concrete structures with small openings or slits (**Figure 4.7**) or with a steel beam, grid, or column framework designed to allow the passage of even more sediment (**Figure 4.8**). In general, the purpose of any open-type check dam is to separate the large volume of solid debris from the transporting fluid (debris-flow breaking) and then selectively retain harmful debris while allowing the finer sediment to pass through and return to the stream (debris-flow retention). Because installation of a large concrete structure is often difficult in remote and rugged terrain, such as the Cornet Creek watershed, recent studies have been conducted in Taiwan on the use of crossing-truss dams, which would not typically require large concrete structures as part of the installation (Wu and Chang, 2003). Crossing-truss dams are generally composed of two rows of overlapping triangular trusses with suitable spacing within an impact row to serve as debris-flow breakers (**Figure 4.9**). The overlap spacing between the impact row and outlet row is designed to help generate a separation between solids and fluid (Wu and Chang, 2003; MEI, 2008).

Although check and crossing-truss dams have been successful in retaining material associated with debris flows, they do require significant construction and maintenance efforts, which would be difficult considering the limited access in the Cornet Creek basin. In the early 1970s, wire net dams were first studied as potential debris-flow barriers that were more cost effective and easier to install. Unfortunately, initial designs consisted primarily of a net developed from numerous intersecting cables, which proved to be prone to failure. Recent advancements, however, have developed a new technique for creating flexible debris-flow barriers that have already been shown to perform successfully under real debris-flow conditions (Tabata et al., 2004).

The modified type of flexible debris-flow mitigation measure was developed from the use of a ring net, which is made by continuously weaving or interlocking multiple rings of steel coils to form a catchment mesh. The result is that rather than the force of a debris flow being concentrated on a single cable as in original designs, it now distributed throughout the rings (**Figure 4.10**) (Tabata et al., 2004). Additional energy-absorption devices, such as heavy-duty load cells placed near anchor locations, deform during an event to help dissipate energy (Wendeler et al., 2005, 2008a).

The use of flexible ring-net barriers is more appropriate in somewhat narrow torrent channels, but they can be easily installed up to widths of about 50 feet without support posts, and up to 100 feet with the addition of support posts (**Figure 4.11**) (Volkwein et al., 2008). The range of application of this system is typically limited by a maximum volume of about 1,300 cubic yards and a maximum flow velocity of almost 20 fps (**Figure 4.12**). However, special net barrier designs with very strong cable supports and concrete abutments have been designed to capture up to 4,000 cubic yards of material (Roth et al., 2004). The two largest recorded debris-flow events from the Cornet Creek basin occurred in 1914 and 1969, and could have possibly transported as much as 25,000 cubic yards of material (MEI, 2008). Obviously, flexible ring-net barriers do not have the capacity to capture material from events similar those in 1914 and 1969, but they could have easily retained the amount of sediment that was conveyed by the July

2007 flood event. Therefore, if properly designed, the use of flexible ring-net barriers appears to be well suited to environments such as the Cornet Creek basin.

Figure 4.7. Concrete slit-type sabo dam. Steel bars were installed at the slit after debris flow was found to pass through the slit (Photo 5; Mizuyama [No 1], 2008).

Figure 4.8. Concrete and steel pipe sabo dam. (Photo 4; Mizuyama [No 1], 2008).

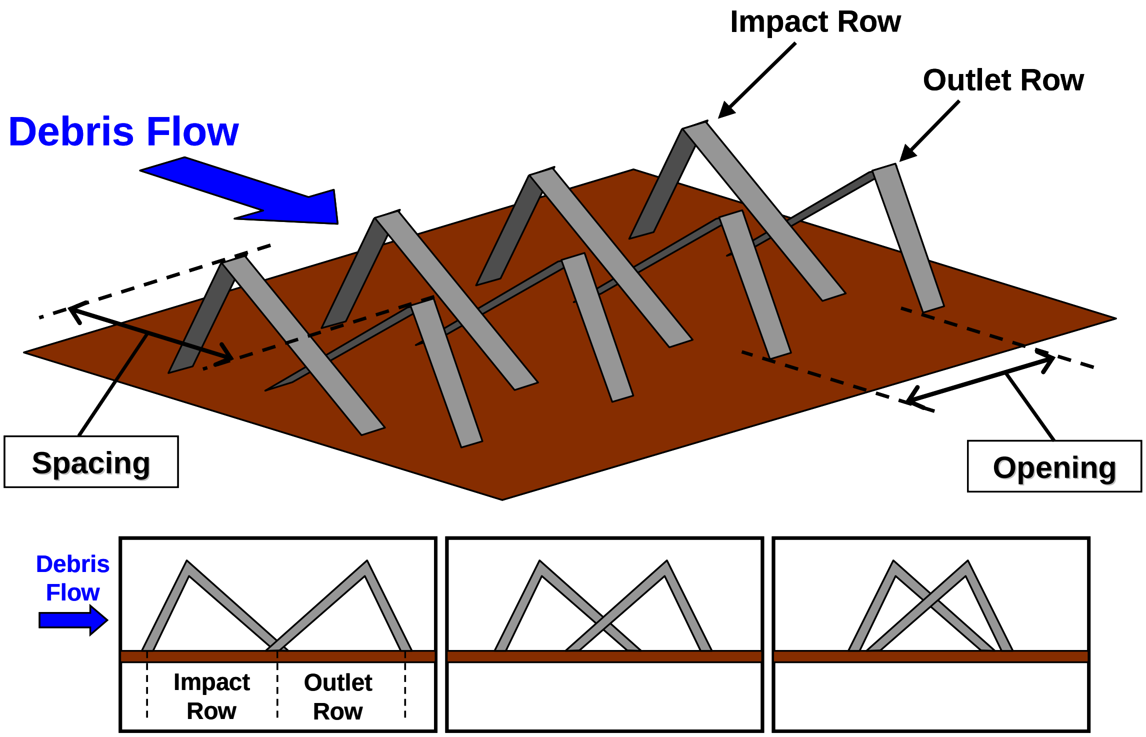

Figure 4.9. Schematic example of crossing-truss dam configuration (modified from Wu and Chang, 2003).

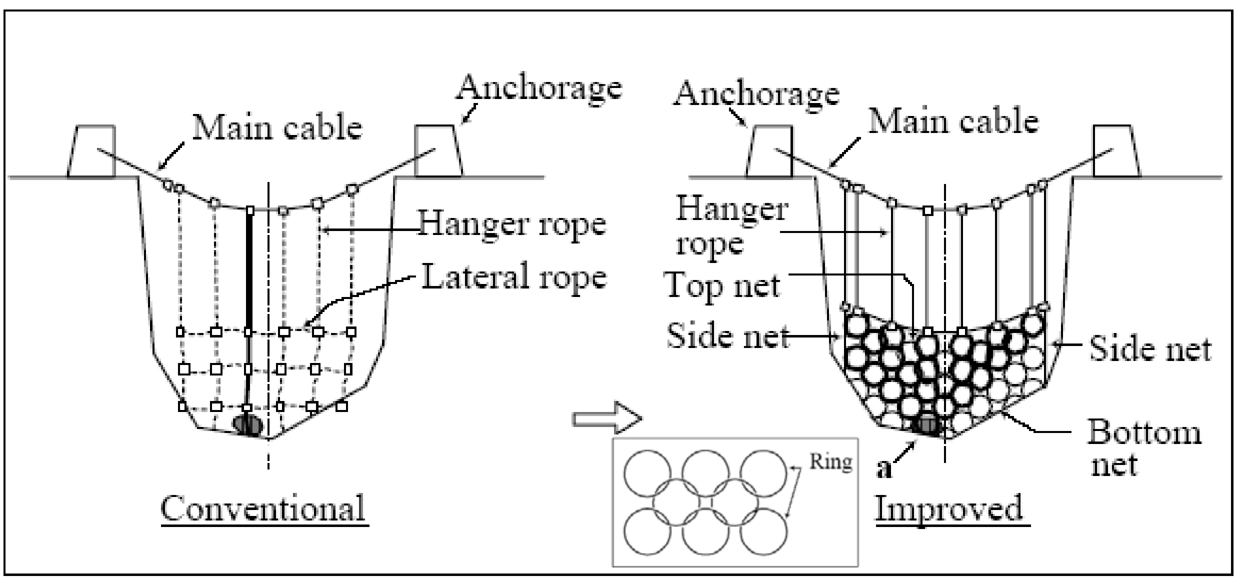

Figure 4.10. Example schematic of conventional and improved (ring-net) flexible debris-flow barriers (modified from Tabata et al., 2004).

Figure 4.11. Example of flexible ring-net debris-flow barrier before (left) and after (right) debris-flow event (Figure 3; Wendeler et al., 2008b).

Figure 4.12. Example of flexible ring-net barrier after debris-flow event. Approximately 980 cubic yards of material is retained by barrier in photo (Figure 1; Roth et al., 2004).

The main advantage of a flexible barrier compared to a massive steel or concrete structure is the light weight which allows for an easier installation, especially in areas where access is limited. Debris-flow protection projects have shown that flexible barriers can be 50 percent more cost efficient than rigid structures, and since the flexible barriers are much more transparent, they also blend better into the landscape (Roth et al., 2004). Another advantage is that it might be possible to tie event trigger sensors such as trip wires to these structures to send an alert if a significant amount of material has been captured.

4.5. Summary

History has shown that the Town of Telluride is at risk from mudflow (debris flow) events that originate from the Cornet Creek watershed. An evaluation of hazard management techniques (countermeasures) that have been successful at mitigating threats caused by debris flows in debris flow-prone areas of the world has shown that some techniques may be applicable, in some form, to the Town of Telluride as well. In general, an early-warning decision support system that utilizes available information, accumulation of debris source material, and meteorological monitoring to provide community outreach and education in the form of hazard outlooks, watches, or warnings, has the potential to reduce the risk to public safety. In addition, flexible structural measures might be useable to mitigate the impact of at least moderate-sized debris flows. Realistically, there are no feasible structural measures that could be installed in the lower reaches of Cornet Creek above the fan apex that could successfully mitigate the larger magnitude events.

5. SUMMARY AND RECOMMENDATIONS

5.1. Summary

The Cornet Creek alluvial fan, upon which the Town of Telluride has been built, has been subjected to large and relatively infrequent debris flows (mudflows) in the last 100 years. The eastern part of the Town was inundated by a debris flow in 1914 and the western portion of the Town was inundated in 1969. Considering the degree of development that has occurred on the fan since both the historical events occurred, it is highly likely that the damages to life and property would be much higher today than they were in 1914 and 1969. Based on the occurrence of these two events in the last 100 years it might be argued that the probability of occurrence of a large debris flow (mudflow) on the Cornet Creek fan is approximately 2 percent in any given year. However, the probability of occurrence of a debris flow is not an independent, random event in the same way that runoff floods are assumed to be. Probability of occurrence of a debris flow (mudflow) is in fact conditional on the accumulation of transportable debris within the basin, antecedent soil moisture conditions within the basin and high intensity triggering rainfall. Conservatively, the frequency of a debris flow (mudflow) event can be assumed to be equal to the probability of the exceedence for a triggering rainfall event, since the probability of exceedence of the mudflow can be no greater than that for the rainfall.

FLO-2D modeling of the bulked hydrographs for the 10- and 25-year recurrence interval peak flows on the Cornet Creek fan under three different scenarios enabled the potential hazard from debris flows (mudflows) to be evaluated. Under Scenarios 1 and 2, the western side of the fan would be inundated during the 25-year event. The area of inundation would be similar to that in the 1969 event and the highest hazard potential is located along the historic course of Cornet Creek that was realigned and channelized following the 1969 event. Under Scenario 1 (Townsend Street Bridge blocked) about 36 acres would be inundated, of which about 4.5 acres would be in a High Hazard Potential zone and about 15 acres would be in a Moderate Hazard Potential zone. Under Scenario 2 (all of the bridges and culverts blocked) about 45 acres would be inundated, of which about 14 acres would be in a High Hazard Potential zone and about 20 acres would be in a Moderate Hazard Potential zone. Under Scenario 3, the eastern side of the fan would be inundated during the 10-year event, based on the assumption that the dike constructed after the 1914 event had failed or was overtopped. Under Scenario 3, about 68 acres would be inundated, of which about 20 acres would be in a High Hazard Potential zone and about 16 acres would be in a Moderate Hazard Potential zone.

Countermeasures to mitigate the impacts of debris flows (mudflows) fall into four categories:

1. Hazard Impact Assessments
2. Advance (early) Warning Systems
3. Event (real-time) Warning Systems
4. Structural Mitigation Measures

The results of the FLO-2D modeling provide a basis for a hazard impact assessment. Advance (early) warning systems have limited forecast accuracy and hence there is a high potential for false alarms. However, depending on the amount of information that is available, which is closely related to cost, it is possible to identify warning thresholds of varying sensitivity. Event (real-time) warning systems can be installed, but they are likely to provide very short warning times given the conditions in the Cornet Creek basin and the likely velocities of the flows. Given the lack of access to the Cornet Creek basin, it is unlikely that major debris flow retention structures could be built and maintained upstream of the fan apex. However, flexible structures could be built and maintained near the fan apex, which would be able to reduce the impacts of small, more frequent events, such as the July 2007 event.

5.2. Recommendations

The following recommendations are made based on the results of this investigation:

1. Development of an early-warning system based on community-accepted levels of risk and uncertainty.

2. Installation of a real-time, event-triggered system that is connected to public warning systems and likely preferred flow paths.

3. Construction of a flexible ring-net barrier near the apex of the fan and reinforcement of the dike at the head of the fan with material trapped by the barrier.

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